Woodhead Publishing Series in Civil and Structural Engineering

Performance of Bio-based Building Materials

Edited by Dennis Jones and Christian Brischke

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

WP
WOODHEAD
PUBLISHING

Performance of Bio-based Building Materials

Related titles

Polymer Modified Bitumen
(ISBN 978-0-85709-048-5)

Solar Energy in Buildings
(ISBN 978-0-12-410514-0)

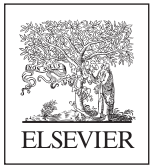
Sustainable Communities Design Handbook
(ISBN 978-1-85617-804-4)

Woodhead Publishing Series in Civil and Structural Engineering

Performance of Bio-based Building Materials

Edited by

Dennis Jones
Christian Brischke



WP
WOODHEAD PUBLISHING
An imprint of Elsevier

Woodhead Publishing is an imprint of Elsevier
The Officers' Mess Business Centre, Royston Road, Duxford, CB22 4QH, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States
The Boulevard, Langford Lane, Kidlington, OX5 1GB, United Kingdom

© 2017 Elsevier Ltd. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices
Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-0-08-100982-6 (print)
ISBN: 978-0-08-100992-5 (online)

For information on all Woodhead publications visit our website at https://www.elsevier.com/books-and-journals

Publisher: Matthew Deans
Acquisition Editor: Gwen Jones
Editorial Project Manager: Charlotte Cockle
Production Project Manager: Omer Mukthar
Cover Designer: Miles Hitchen

Contents

List of contributors **ix**
Preface **xiii**
Acknowledgement **xv**

1 Introduction to the performance of bio-based building materials **1**
D. Jones
1.1 Introduction **1**
1.2 Bio-based building materials and their role in the modern building sector **2**
1.3 Use in construction and legislation **4**
1.4 Current issues and challenges related to performance of bio-based building materials **10**
References **15**

2 Wood as bio-based building material **21**
2.1 Introduction **21**
C.-M. Popescu
2.2 Solid wood **22**
B. Mazela, C.-M. Popescu
2.3 Cross laminated timber **40**
P. Wilson
2.4 Panels **52**
S. Curling, J. Kers
2.5 Wood plastic composites **61**
G.A. Ormondroyd, J. Kers
2.6 Cellulose, pulp and paper **68**
C.-M. Popescu, D. Jones
2.7 Bark and cork **78**
H. Pereira, S. Knapic
References **86**

3 Nonwood bio-based materials **97**
3.1 Introduction **97**
L. Nunes
3.2 Flax **98**
R. Réh, M.C. Barbu

3.3 Hemp **105**
R. Réh, M.C. Barbu
3.4 Straw **112**
P. Walker, A. Thomson, D. Maskell
3.5 Bamboo and rattan **120**
S. Knapic, A. Bajraktari, L. Nunes
3.6 Reed **124**
J.M. Greef, C. Brischke
3.7 Wool **128**
E. Mansour, G.A. Ormondroyd
3.8 Peat **142**
T. Teppand
3.9 Grass **150**
T. Teppand
3.10 Vegetal pith **156**
M. Palumbo, A.M. Lacasta
References **174**

4 Protection of the bio-based material **187**
4.1 Introduction **187**
M. Humar
4.2 Potential hazards and degrading agents **188**
C. Brischke, W. Unger
4.3 Material protection **203**
M. Humar, E. Melcher
4.4 Wood modification **211**
S. Bollmus, A. Gellerich, H. Militz
4.5 Coatings and hydrophobes **217**
M. Petrič
4.6 Protection by design and maintenance **228**
C. Brischke, M. Humar, D. Lorenzo
References **240**

5 Performance of the bio-based materials **249**
5.1 Introduction **249**
C. Brischke, M. Humar
5.2 Function **250**
C. Brischke, M. Humar, S. Thelandersson
5.3 Durability **257**
J. Van Acker, S. Palanti
5.4 Moisture performance **277**
C. Brischke
5.5 Aesthetics **285**
A. Sandak, J. Sandak

5.6 Thermal performance **294**
A. Ugovšek, B. Šubic
5.7 Fire performance of bio-based building materials **305**
J. Schmid, M. Klippel, B. Östman
References **320**

6 Performance of buildings **335**
S.L. Bardage
6.1 Introduction **335**
6.2 Building physics **335**
P. Faria, A. Brás
6.3 Energy efficiency **345**
P. Faria, A. Brás
6.4 Indoor air quality **351**
B. Stefanowski, S. Curling, G.A. Ormondroyd
6.5 Bio-based materials and human well-being in the built environment **365**
M.D. Burnard
References **372**

7 Test methods for bio-based building materials **385**
7.1 Introduction **385**
S. Curling
7.2 Laboratory testing **387**
7.2.1 Bacteria, moulds and decay fungi **387**
S. Curling, L.R. Gobakken
7.2.2 Insects **394**
S. Curling
7.2.3 Marine borers **398**
S.M. Cragg
7.2.4 Moisture dynamics **406**
I. de Windt, W. Willems
7.3 Field methods **416**
7.3.1 Decay fungi, staining fungi, mould and bacteria **416**
L. Meyer-Veltrup, L.R. Gobakken
7.3.2 Insects **421**
S. Curling
7.3.3 Marine borers **422**
S.M. Cragg
7.3.4 Moisture dynamics **424**
L. Meyer-Veltrup, J. Van den Bulcke
7.4 Weathering and leaching **428**
E. Melcher, M. Humar
7.5 Monitoring of structures and in-service testing **444**
F. Lanata, N. Macchioni, S. Palanti
References **460**

8 Modelling **483**
8.1 Introduction **483**
C. Brischke
8.2 Mould development **484**
E. Frühwald Hansson
8.3 Hygro-thermal models **495**
S. Fortino
8.4 Modelling of weathering **502**
J. Sandak, A. Sandak, I. Burud
8.5 Decay models **510**
C. Brischke, H. Viitanen
8.6 Mechanical performance modelling **522**
J.W.G. van de Kuilen, W.F. Gard
References **538**

9 Environmental assessment of bio-based building materials **547**
E. Suttie, C. Hill, G. Sandin, A. Kutnar,
C. Ganne-Chédeville, F. Lowres, A.C. Dias
9.1 Introduction **547**
9.2 Environmental assessment of bio-based building materials **548**
9.3 Measurement and certification **565**
References **584**

10 Durability, efficacy and performance of bio-based construction materials: Standardisation background and systems of evaluation and authorisation for the European market **593**
M. Kutnik, E. Suttie, C. Brischke
10.1 European standardisation of durability and performance **593**
10.2 EC regulations related to wood-based and other construction products **604**
References **607**

Glossary **611**
Index **623**

List of contributors

A. Bajraktari University of Applied Science in Ferizaj, Ferizaj, Republic of Kosovo

M.C. Barbu University of Applied Sciences, Kuchl, Austria

S.L. Bardage RISE Research Institutes of Sweden, Stockholm, Sweden

S. Bollmus University of Göttingen, Göttingen, Germany

A. Brás NOVA University of Lisbon, Caparica, Portugal; Current affiliation: Liverpool John Moores University, Liverpool, United Kingdom

C. Brischke Leibniz University Hannover, Hannover, Germany; University of Göttingen, Göttingen, Germany

M.D. Burnard University of Primorska, Koper, Slovenia; Abelium R&D, Ljubljana, Slovenia; InnoRenew CoE, Izola, Slovenia

I. Burud Norwegian University of Life Sciences, Ås, Norway

S.M. Cragg University of Portsmouth, Portsmouth, United Kingdom

S. Curling Bangor University, Bangor, United Kingdom

I. de Windt Laboratory of Wood Technology – Woodlab, Gent, Belgium

A.C. Dias University of Aveiro, Aveiro, Portugal

P. Faria CERIS and NOVA University of Lisbon, Caparica, Portugal

S. Fortino VTT Technical Research Centre of Finland Ltd, Espoo, Finland

E. Frühwald Hansson Lund University, Lund, Sweden

C. Ganne-Chédeville Bern University of Applied Sciences, Biel/Bienne, Switzerland

W.F. Gard TU Delft, Delft, The Netherlands

A. Gellerich University of Göttingen, Göttingen, Germany

L.R. Gobakken Norwegian Institute of Bioeconomy Research (NIBIO), Oslo, Norway

J.M. Greef Institute of Crop and Soil Science, Braunschweig, Germany

C. Hill JCH Industrial Ecology Ltd, Bangor, United Kingdom; NIBIO, Ås, Norway

M. Humar University of Ljubljana, Ljubljana, Slovenia

D. Jones DJ Timber Consultancy plc, Neath, United Kingdom; University of Primorska, Koper, Slovenia; Luleå University of Technology, Skellefteå, Sweden

J. Kers Tallinn University of Technology, Tallinn, Estonia

M. Klippel ETH Zurich, Zurich, Switzerland

S. Knapic University of Lisbon, Lisbon, Portugal; LNEC, Lisbon, Portugal

A. Kutnar University of Primorska, Koper, Slovenia; InnoRenew CoE, Izola, Slovenia

M. Kutnik Technological Institute FCBA, Bordeaux, France

A.M. Lacasta Polytechnic University of Catalonia, Barcelona, Spain

F. Lanata ESB, Nantes, France

D. Lorenzo University of Santiago de Compostela, Lugo, Spain

F. Lowres BRE, Watford, United Kingdom

N. Macchioni CNR IVALSA, Sesto Fiorentino, Italy

E. Mansour Bangor University, Bangor, United Kingdom

D. Maskell University of Bath, Bath, United Kingdom

B. Mazela Poznan University of Life Sciences, Poznan, Poland

E. Melcher Thünen Institute of Wood Research, Hamburg, Germany

L. Meyer-Veltrup Leibniz University Hannover, Hannover, Germany

H. Militz University of Göttingen, Göttingen, Germany

L. Nunes LNEC, Lisbon, Portugal; cE3c/ABG and University of the Azores, Azores, Portugal

G.A. Ormondroyd Bangor University, Bangor, United Kingdom; University of Bath, Bath, United Kingdom

B. Östman Linnaeus University, Växjö, Sweden

S. Palanti CNR IVALSA, Trees and Timber Institute, Sesto Fiorentino, Italy

M. Palumbo Federal Fluminense University, Niterói, Brasil

H. Pereira University of Lisbon, Lisbon, Portugal

M. Petrič University of Ljubljana, Ljubljana, Slovenia

C.-M. Popescu Petru Poni Institute of Macromolecular Chemistry of the Romanian Academy, Iasi, Romania

R. Réh Technical University in Zvolen, Zvolen, Slovak Republic

A. Sandak CNR-IVALSA, Trees and Timber Institute, San Michele all'Adige, Italy; University of Primorska, Koper, Slovenia

J. Sandak CNR-IVALSA, Trees and Timber Institute, San Michele all'Adige, Italy; University of Primorska, Koper, Slovenia

G. Sandin RISE Research Institutes of Sweden, Gothenburg, Sweden

J. Schmid ETH Zurich, Zurich, Switzerland

B. Stefanowski Bangor University, Bangor, United Kingdom

B. Šubic M SORA d.d., Žiri, Slovenia

E. Suttie BRE, Watford, United Kingdom

T. Teppand Estonian University of Life Sciences, Tartu, Estonia

S. Thelandersson Lund University, Lund, Sweden

A. Thomson BRE Centre of Innovative Construction Materials, Garston, United Kingdom

A. Ugovšek M SORA d.d., Žiri, Slovenia

W. Unger University of Applied Sciences Potsdam, Potsdam, Germany

J. Van Acker Ghent University (UGent), Ghent, Belgium

J.W.G. van de Kuilen TU Delft, Delft, The Netherlands; TU München, München, Germany

J. Van den Bulcke Laboratory of Wood Technology – Woodlab, Gent, Belgium

H. Viitanen Aalto University (Docent), Espoo, Finland; VTT Technical Research Centre of Finland Ltd, Espoo, Finland; (Senior Research Scientist; Emeritus)

P. Walker BRE Centre of Innovative Construction Materials, Garston, United Kingdom; University of Bath, Bath, United Kingdom

W. Willems Firmolin, Deurne, The Netherlands

P. Wilson Timber Design Initiatives Ltd, Edinburgh, United Kingdom

Preface

The ‘bio-based economy’ represents an increasing area of development globally and covers a wide range of activities incorporating bio-based materials. ‘Bio-based’ in this context means that the materials and products are derived/made from renewable resources, with the criteria that a renewable resource recovers faster than it is drained, in contrast to many mineral and fossil resources. The processing of the forest biomass into value-adding and durable building materials and products, also taking into account the by-product streams, clearly fulfils these criteria today and with proactive strategies also in the future. In addition to this, compared with aluminium, steel and concrete, most such bio-based materials are made with considerable lower energy consumption, and their use acts as a carbon sink, which means that a replacement of materials made from nonrenewable resources directly reduces CO_2 emissions. The future strategies for the world's energy and material supply must consider these facts since some prognoses indicate that the fast growth of the bioenergy sector could result in a higher use than growth of Europe's forest and agricultural biomass.

The development of building materials incorporating bio-based materials is also an area of rapid development. Solid timber, wood fibres and other materials, such as bamboo, miscanthus, phragmites and other gramineae, are now being used for structural purposes and for roofing and cladding, and there are many textbooks and reference articles related to their use. In particular, the combined use of wood-based and other bio-based materials allows the configuration of diverse composites, such as particle and fibreboards, sandwich panels or in combinations with polymers as extruded profile members (*WPC* and *BPC*) and shaped components. Traditional agricultural food plants also have the potential being used for various building applications, for example, lightweight building boards or insulation wall fillings. Flax, hemp, sisal, coir, corn cobs and rice or wheat straw are just a few examples of biofibres used in different applications in the building trade. Wood itself is not only used in its native character but also chemically and thermally modified. Finally, the use of classical and new preservatives allows the use of timber products even under severe outdoor exposure conditions.

This textbook represents one of the key outcomes from *COST* Action FP1303 (Performance of bio-based building materials). Founded in 1971, COST (European Cooperation in Science and Technology) is the first and widest European framework for the transnational coordination of nationally funded research activities. COST enables breakthrough scientific developments leading to new concepts and products and thereby contributes to strengthen Europe's research and innovation capacities. It is a unique means for European researchers to jointly develop their own ideas and new

initiatives across all scientific disciplines through trans-European networking of nationally funded research activities. Among the key features of COST are

- building capacity by connecting high-quality scientific communities throughout Europe and worldwide
- providing networking opportunities for early career investigations
- increasing the impact of research on policymakers, regulatory bodies and national decision makers, as well as the private sector

The book reviews many of the key properties of bio-based materials and how these materials are becoming materials of choice within modern construction methods. It will consider the current needs and how materials are currently being used, with emphasis on how the material performs during its service life. It brings together the combined knowledge and expertise across the European scientific community leading activities into the use of bio-based materials within construction and aims to provide guidance to these materials and how they perform when used correctly.

Dennis Jones
Christian Brischke

Acknowledgement

European Cooperation in Science and Technology (*COST*) is a pan-European intergovernmental framework. Its mission is to enable breakthrough scientific and technological developments leading to new concepts and products and thereby contribute to strengthening Europe's research and innovation capacities. It allows researchers, engineers and scholars to jointly develop their own ideas and take new initiatives across all fields of science and technology while promoting multi- and interdisciplinary approaches. COST aims at fostering a better integration of less research-intensive countries to the knowledge hubs of the European research area. The COST Association, an international not-for-profit association under Belgian Law, integrates all management, governing and administrative functions necessary for the operation of the framework. The COST Association has currently 36 member countries (www.cost.eu).

'This book is based upon the work from COST Action (FP1303, performance of bio-based building materials)'.

This page intentionally left blank

Introduction to the performance of bio-based building materials

1

D. Jones[*,†,‡]
[*]DJ Timber Consultancy plc, Neath, United Kingdom, [†]University of Primorska, Koper, Slovenia, [‡]Luleå University of Technology, Skellefteå, Sweden

1.1 Introduction

It is recognised that the construction market is one of the major employment sectors globally. It was estimated in 2016 that the sector provided direct employment to around 18 million jobs across the European Union (*EU*) alone (European Commission, 2016). This comprises approximately 75% construction enterprises (many of which were micro- to medium-sized enterprises), which combined a turnover of approximately 9% of the EU-27 *GDP*. Whilst the construction sector faced a significant downturn in activities and income due to the economic downturn between 2005 and 2014, there is a continued demand for new and/or improved housing. Current suggestions predict a significant upturn in construction activities, with some predictions indicating the global sector will grow by approximately 4.3% per year to 2025 (UK Govt, 2013). This is being further affected by increased awareness into resource efficiency and performance. This has led to a reconsideration of approaches to issues such as energy, climate change, impacts on natural resources (energy, water and materials) and public convenience and welfare (accessibility, safety, security, indoor air quality, etc.). This is relevant not only to new building programmes but also to the existing building stock (where the greatest levels of change may be achieved). Demands for improved building stock are greater in certain areas globally, as typified by suggestions for the needs in India, where the sector is expected to be worth US $0.6 trillion a year by 2020 and 170 million new homes built by 2030 (ITE Build and Interiors, 2015). These demands place ever-increasing demands on supplies of materials, which has helped fuel an increased demand for sustainable construction.

Sustainable construction as defined by the European Commission's (*EC*) 'lead market initiative for Europe—midterm progress report' (European Commission, 2009) is the dynamic for developing new solutions involving investors, construction industry, professional services, industry suppliers and other relevant parties towards achieving sustainable development, taking into consideration environmental, energy, socioeconomic and cultural issues. This initiative focussed on nonwood and pulp resources, though many of the concepts could easily be applied to what are perceived as traditional resources. It embraces a number of aspects such as design and management of buildings and constructed assets, choice of materials, energy use of the physical and functional performances of building and interaction with urban and economic development and management. A key means of achieving desired levels of increased

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00001-X
© 2017 Elsevier Ltd. All rights reserved.

sustainable construction is through a greater use of bio-based resources in innovative products, as demonstrated by the EU Commission's bioeconomy strategy of 2012 (European Commission, 2012). Within the context of this book, bio-based resources refer to plant-, tree- and animal-derived materials, either in their sourced format or resulting from modification or treatment or from incorporation into other materials (e.g., in the form of composites, though this has been the focus of a recent publication) (Fan and Fu, 2016).

The following sections will consider current and future demands for bio-based materials within construction, before subsequent chapters consider the range of bio-based materials and their performance in service.

1.2 Bio-based building materials and their role in the modern building sector

The use of bio-based materials has been of major importance throughout human history, mainly due to abundance, ease of use and adaptability, relative simplicity to use and sustainability. The advantages of these bio-based materials are that they are renewable, almost globally distributed in a variety of forms, easily sourced, readily adapted to the needs and use, hydroscopic, recyclable, versatile, porous and nonabrasive. Also, as a result of their nature, they are biodegradable, combustible, compostable and reactive. However, the properties that may be seen as detrimental can be controlled through correct use and detailing and help in the ultimate disposal through natural processes (i.e., no release of so-called toxic materials).

As indicated above, bio-based materials present us with the capability to mimic and exploit properties that have evolved in nature to provide certain performance characteristics. Bio-based materials have the potential to provide construction materials with the following benefits:

- The capture and storage of carbon extracted from atmospheric CO_2 through recent photosynthesis.
- Sustainable production as crops grown annually or as longer harvest-cycle foresting, including secondary products from food growth.
- Biodegradability at end of service life (controlled decay inside an anaerobic digester would produce both organic fertiliser and biomethane to supply energy).
- Exceptionally low or almost zero linear coefficients of thermal expansion, often comparable or better than many man-made products.
- The property of controlling temperature and humidity in enclosed spaces as a direct result of phase changes of water and moisture within cell walls.
- High vapour diffusivity and ‘Fickian’ vapour dispersal.
- Relatively high specific heat capacity.
- Low thermal diffusivity.
- Excellent performance-to-weight ratios.
- Overall lower embodied energy (*EE*) than man-made or synthetic materials.

Society through the ages has had differing demands within our built environment, whereby technological advances led to uses of different materials over the ages.

Table 1.1 Recent advancement of EOD

Year	Overshoot day	Year	Overshoot day
1970	Dec. 31	2010	Aug. 21
1987	Dec. 19	2011	Aug. 27
1990	Dec. 7	2012	Aug. 22
1995	Nov. 21	2013	Aug. 20
2000	Nov. 1	2014	Aug. 19
2005	Oct. 20	2015	Aug. 13
2007	Oct. 26	2016	Aug. 8
2008	Sep. 23	2017	Aug. 3
2009	Sep. 25	2030	Jul. 2

During the middles ages, the use of bio-based materials was slowly replaced with more permanent structures using stone, whilst the industrial revolution led to a greater variety of materials, which became material of choice as technology advanced. The nineteenth century focussed more on the use of iron and steel, which was then superseded by the use of concrete and glass in the twentieth century. Whilst these industries provide impressive structures within our cities and surroundings, it has become apparent that demand for resources is outstripping supply. This has been demonstrated in recent years through the determination of the Earth overshoot day (*EOD*), which was previously known as the ecological debt day (*EDD*) (Wackernagel *et al.*, 2002). If the EOD is defaulted to 31 Dec. 1970, Table 1.1 shows how we have been progressively increasing the demand on global resources, with significant advancing on these resources in the past 25 years.

Estimates suggest if this trend continues unabated, we will require the equivalent of two planet Earths annually by 2030. This allows the extrapolation of the EOD to be on Jul. 2. Improving resource efficiency can suppress this demand and will increase the use of sustainable materials. This is typified by drives towards more energy-efficient construction methods, culminating in Passivhaus construction, which in its original approach, focused on reducing demands within new and existing building stock under 15 kWh/m^2 and less than 25 kWh/m^2, respectively, for each group. The planned reductions in energy consumption were proposed via thicker insulation layers, considerably improved airtightness, implementation of heat exchange during air exchange and prevention of cold bridging within construction design. The development in energy improvement levels is shown in Fig. 1.1, which outlines how international building regulations have dictated greater performance levels in recent years. Greater detail into individual values in building regulations is shown in Table 1.2 (Jones *et al.*, 2011).

In addition to the changes in building regulations, the implementation of the energy performance of buildings directive (European Commission, 2003) has led to all EU member states to aim at reducing the carbon emissions from building stocks by 90% by 2050 (Emission Commission, 2011). This represents a challenging aim and covers both emissions from regulated and nonregulated (i.e., anything plugged in) and the combined level effectively representing the total operational energy consumption of the building in question.

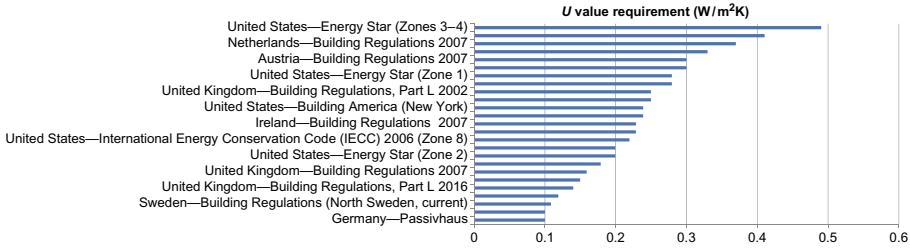


Fig. 1.1 Graphical indication of the improvement in *U*-value requirements in construction.

The use of wood- and plant-based materials are recognised as a means of overcoming many of the issues related to increasing carbon dioxide emissions from construction through their beneficial contributions to health, indoor air quality and sustainability factors (Amziane and Sonebi, 2016). Global warming, energy savings, and life-cycle issues are factors that have contributed to the rapid expansion of plant-based materials for buildings, which can be qualified as environmental friendly and efficient multifunctional materials. An analysis of the predictive input of different energy demands for past, current and future buildings in terms of environmental impacts suggests that the manufacture of building materials has the greater input under current conditions (Fig. 1.2). This work (Peuportier, 2008; Magniont, 2010) considered the most effects of energy contribution when overall consumption decreases from 200 to 15 kWh/m^2 year, where these impacts may be impacted greater through the use of bio-based materials.

1.3 Use in construction and legislation

In order to ensure safety, every country has implemented building regulatory systems, comprising building regulations and building control system. The purpose of building regulations is to ensure a guaranteed quality level. Through their implementation and enforcement, people are assured of safe, healthy, accessible and energy-efficient buildings. The format of the building regulations often depends upon the national structure and local government policies. A recent study (Pedro *et al.*, 2010) reviewed the national regulations across EU countries, whereby legislation may be defined at regional or national levels. Regardless of the governing body creating the legislature, all construction within each respective country had to adhere to the defined parameters. Whilst these rules are still in place, a pan-European legislation has been adopted, namely, eurocodes.

Overall, there are ten main eurocodes, and their subsequent subcodes that provide a common approach for the design of buildings and other civil engineering works and construction products are shown in Table 1.3. Those displayed in italics are not directly related to bio-based materials in construction, though it should be considered when designing and constructing with hybrid material systems.

In addition to the eurocodes and national standards, there are secondary European Technical Approval Guidelines (*ETAGs*) that were established by the European Organisation of Technical Approvals under the Construction Products Directive

Table 1.2 Comparison of properties of selected building elements from some European building regulations (Jones *et al.*, 2011)

Maximum permitted value	United Kingdom Building Regulations Part L (2006)	United Kingdom Code for Sustainable Homes (*CSH*) Level 4	United Kingdom Code for Sustainable Homes (CSH) Level 6	Denmark Building Regulations (2010)	Denmark High Performance Building Regulations (2020)	Passivhaus requirement
U value of exposed building element						
Roof systems (W/m^2K)	0.16–0.25	0.13	0.13	0.20	0.20	≤0.15
Walls (W/m^2K)	0.35	0.20	0.15	0.30	0.30	≤0.15
Floor (W/m^2K)	0.25	0.20	0.15	0.20	0.20	≤0.15
Windows, doors, and roof lights (timber or *PVC*) (W/m^2K)	2.2	1.5	0.7	1.8	0.8–1.2	≤0.85
Air tightness ($m^3/(h\,m^2)$)	10	3	1	5.4	1.8	0.6

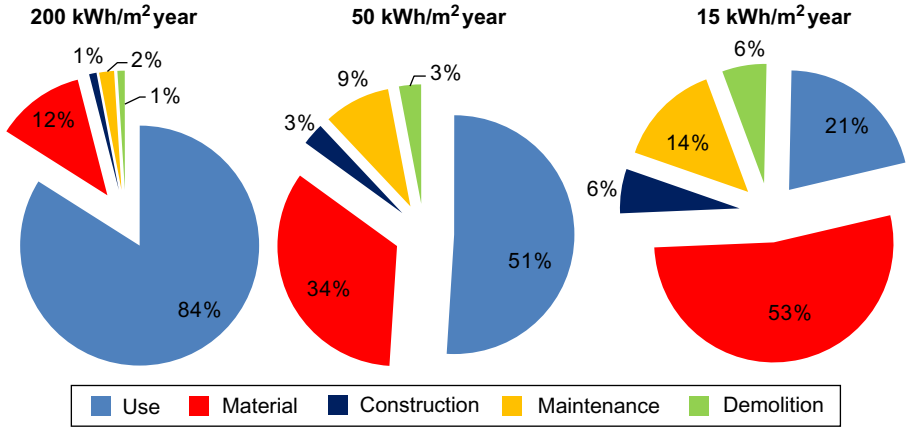


Fig. 1.2 Distribution of environmental impacts with improving energy performances of buildings.

(*CPD*), which was replaced by EU regulation 305/2011 (OJEU, 2011). Of the 35 ETAGs to date, several of these can be directly applied to bio-based building materials.

In almost all EU countries, there is a building act that provides the legal framework for legislation concerning the content and implementation of building regulations. The building act usually includes the main requirements for construction works, the procedures for design, a description of building and operation of construction works, the list of competences of national and local authorities and the tasks and responsibilities of persons participating in a construction project.

To assist these building acts and standardised methods of construction, there are a range of assessment methods for determining the overall performance of a building. Table 1.4 gives an overview of some of the main methods being used at present.

As standardisation and assessment methods become more coordinated, there is a drive towards focusing on a limited number of methods, with the two main methods being BRE Environmental Assessment Method (*BREEAM*) and Leadership in Energy and Environmental Design (*LEED*) globally, and methods such as *DGNB* and *HQE*, among others, are less commonly used methods in Europe.

BREEAM is now the world's leading and most widely used environmental assessment method for buildings (Crawley and Aho, 1999; BREEAM, 2008). The tool helps set the standards for best practise in sustainable design and is the *de facto* measure used to describe a building's environmental performance. The aim of BREEAM is to primarily provide clients, developers and designers with

- market recognition for low environmental impact buildings
- assurance that best environmental practise is incorporated into a building
- inspiration to find innovative solutions that minimise the environmental impact
- a benchmark that is higher than regulation
- a tool to help reduce running costs, improve working and living environments
- a standard that demonstrates progress towards corporate and organisational environmental objectives

Table 1.3 List of eurocodes relevant to bio-based building products

Title	Reference
Eurocode: basis of structural design	CEN (2002a)
Eurocode 1: actions on structures	
Part 1-1: general actions—densities, self-weight, imposed loads for buildings	CEN (2002b)
Part 1-2: general actions—actions on structures exposed to fire	CEN (2002c)
Part 1-3: general actions—snow loads	CEN (2003b)
Part 1-4: general actions—wind actions	CEN (2005a)
Part 1-5: general actions—thermal actions	CEN (2003c)
Part 1-6: general actions—actions during execution	CEN (2005b)
Part 1-7: general actions—accidental actions	CEN (2006a)
Part 2: traffic loads on bridges	CEN (2003a)
Part 3: actions induced by cranes and machinery	CEN (2006b)
Part 4: silos and tanks	CEN (2006c)
Eurocode 2: design of concrete structures	CEN (2004a,b), CEN (2005c), and CEN (2006d)
Eurocode 3: design of steel structures	CEN (2005d,e,f,g,h), CEN (2006e,f,g,h,i,j,k), and CEN (2007a,b,c,d,e,f,g,h)
Eurocode 4: design of composite steel and concrete structures	CEN (2004c), CEN (2005i,j)
Eurocode 5: design of timber structures	
Part 1-1: general—common rules and rules for buildings	CEN (2004d)
Part 1-2: general—structural fire design	CEN (2004e)
Part 2: bridges	CEN (2004f)
Eurocode 6: design of masonry structures	
Eurocode 7: geotechnical design	
Eurocode 8: design of structures for earthquake resistance	
Part 1: general rules, seismic actions and rules for buildings	CEN (2004g)
Part 2: bridges	CEN (2005i,j,k)
Part 3: assessment and retrofitting of buildings	CEN (2005l)
Part 4: silos, tanks and pipelines	CEN (2006l)
Part 5: foundations, retaining structures and geotechnical aspects	CEN (2004h)
Part 6: towers, masts and chimneys	CEN (2004i)
Eurocode 9: design of aluminium structures	

Table 1.4 Overview of some assessment tools used in a variety of countries

Country	Name of assessment tool	Country	Name of assessment tool
Australia	Nabers/Green Star	Italy	Protocollo Itaca
Brazil	*AQUA*/LEED Brasil	Mexico	LEED Mexico
Canada	LEED Canada/Green Globes	New Zealand	Green Star NZ
China	GB Evaluation standard for green building	Portugal	Lider A
Finland	PromisE	Spain	VERDE
France	HQE and Carbon Site	The United Kingdom	BREEAM/Code for Sustainable Homes
Germany	DGNB	The United States	LEED
Israel	SI-5281		

BREEAM addresses wide-ranging environmental and sustainability issues and enables developers and designers to prove the environmental credentials of their buildings to planners and clients. It uses a straightforward scoring system that is transparent, easy to understand and supported by evidence-based research. Overall, it has a positive influence on the design, construction and management of buildings and helps set and maintain robust technical standards with alongside quality assurance and certification.

Originally developed for the UK construction sector, BREEAM is now used all around the world and can be used to assess a single development or a portfolio of developments both within and across national boundaries. BREEAM Europe and BREEAM Gulf already exist, with the likelihood of more regional variants to follow in the near future. BREEAM has a particular benefit in that it can be readily adapted to local regulation and conditions. Specific versions of BREEAM are available for the United Kingdom, the Gulf and Europe and can incorporate local codes and standards.

LEED green building rating system is an assessment method founded by and run by the US-based Green Building Council (*USGBC*). The USGBC was founded in 1993 and is a national, not-for-profit, membership organisation. The LEED programme was first implemented in 1998 as a voluntary, consensus-based national standard for developing high-performance, sustainable buildings. The assessment is based on a point system for a building being rated, with points awarded in a number of environmentally related categories, including site factors, water efficiency, materials and resources and indoor air quality. The material and resource section of LEED allows for a greater use of renewable and bio-based products. This comes at a time when the use of bio-based materials in construction has reduced from 40% to 8% in the past century (Matos and Wagner, 1998).

Deutsche Gesellschaft für Nachhaltiges Bauen e.V. (DGNB—German Sustainable Building Council) is an assessment tool covering all of the key aspects of sustainable

building: environmental, economic, sociocultural and functional aspects, technology, processes and the site with certification provided at three different levels (gold, silver and bronze). The first four quality sections have equal weight in the assessment. This means that the DGNB System is the only one that gives as much importance to the economic aspect of sustainable building as it does to the ecological criteria. The assessments are always based on the entire life cycle of a building and the performance of the building. This means that DGNB provides a continual performance assessment for materials in use, complementing the advances in bio-based materials being promoted herein.

Haute Qualité Environnementale (HQE, High Quality Environmental standard) was developed as a result of the 1992 Earth Summit and is the assessment standard for green building in France. The key themes of HQE are managing the impacts on the outdoor environment and measuring the indoor quality of a building. HQE can apply to tertiary buildings, individual homes or to blocks of group accommodation. The assessment process is a top-down methodology and that it works from the aims of the project to help define the materials to be used.

Table 1.5 gives an overview of some of the key factors in four assessment tools. From this table, it can be seen that no two assessment methods are the same. Each has its own series of key criteria and relative weightings to determine the effects of each category.

In recent years, there have been discussions aimed at harmonising the assessment tools, but this has proved hard to achieve given the differing regulations in different countries. There may be greater opportunities for harmonisation with the adoption of multinational codes and standards (as with eurocodes across Europe), though this may take several years to come to fruition.

Table 1.5 Comparison of four assessment tools used in the certification of buildings

BREEAM	LEED	DGNB	HQE
Management	Sustainable site	Ecological quality	Eco-construction
Health and well-being	Water efficiency	Economical quality	Eco-management
Energy	Energy and atmosphere	Sociocultural quality	Comfort
Transport	Materials and resources	Process quality	Health
Water	Indoor environmental quality	Site use	
Materials	Innovation and design process		
Waste			
Land use and ecology			
Pollutants			
Innovation			

1.4 Current issues and challenges related to performance of bio-based building materials

Recent developments have seen an increase in awareness of the potential for bio-based building materials in modern society. One of the key factors regarding bio-based building materials is that they are made from plant-derived substances that can be produced repeatedly. This is in contrast to most standard construction materials developed or used over the last 200 years, as they have typically been derived from nonrenewable raw materials, such as oil, minerals and metals. Renewable construction materials range from very traditional 'natural' unprocessed materials such as straw bales used for walling (as discussed in Section 3.4), to more refined products such as floor coverings manufactured using renewable polymers and modern engineered wood products such as cross-laminated timber (Section 2.3). Renewable materials are beginning to be introduced into mainstream construction, for example, hemp and lime walling material (Section 3.3.3), along with the use of plant fibres in concrete.

1.4.1 The sustainable agenda

The combination of resource efficiency and environmental credentials has led to an increase in opportunities for bio-based materials at the start of the twenty-first century. Urbanisation is playing a greater part in human demographics, such that approximately 80% of our time is now spent within buildings, so comfort and functionality play a greater role in societal prosperity. How buildings perform, their levels of comfort and how they affect health and well-being all need to be considered in our modern society—not only for new-build construction but also for retrofitting and refurbishment of existing building stock. The consideration of more sustainable materials within our society contributes to a greater circular economy through a sustainable agenda.

Through the over exploitation of raw material resources and extensive use of energy-intensive materials, there is a continual drain on energy and material resources that can adversely affect the environment. However, these demands raise living conditions globally. There is a need for energy-efficient, environment friendly and sustainable building alternatives, with a focus on

- energy conservation
- minimising the use of high-energy materials
- minimise transportation and maximise the use of local materials and resources
- decentralised production and maximum use of local skills
- utilisation of industrial and mine wastes for the production of building materials
- recycling of building wastes
- use of renewable energy sources

The need to engage in greater sustainability within modern society has been recognised by levels in climate change, which led to the first world climate conference in 1979. The following two decades saw several meetings of the Intergovernmental Panel on Climate Change (*IPCC*), culminating in the UN Framework Convention on Climate Change coming into force in 1994, and the adoption of the Kyoto Protocol in 1997.

Subsequent meetings of the IPCC and other groups led to recommendations such as the Washington declaration in 2007 and the Cancun agreement in 2010. The need to modify the Kyoto Protocol has ultimately led to the Doha agreement in 2012 and the Paris agreement, which came into force on 4 Nov. 2016. Key to these agreements is the need to reduce greenhouse gases, and one of the key contributors to this is the current global building stock, in terms of their energy requirements for comfortable living conditions and the EE within the constructions themselves. It has been estimated that buildings account for more than 40% of global energy consumption and as much as 33% of carbon dioxide equivalent emissions (UNEP SBCI, 2009), in particular related to the increased use of cementitious products in construction (with cement production in 2014 estimated 4.3 billion tonnes globally). This effect has been determined accounting to 8.1 Gt annually (*IEA*, 2011). The International Energy Agency (IEA) baseline scenario for the building sector in 2050 predicts global emissions of 15.2 Gt annually should there not be any corrective action but identifies potential reductions of as much as 12.6 Gt through adoption of their proposed variety of strategies, which can be enhanced by aggressive policy action.

The acceptance of bio-based building materials within the construction often depends upon increasing the perception of the materials in question. This is dependent upon increasing consumer knowledge and creating stronger links between architects, specifiers, and local and national authorities so that the following may be considered effectively:

- influence of environmental considerations
- influence of material performance
- evaluation of life-cycle costs
- understanding of claims by manufacturers
- implications within tenders

Combining these factors defines the following questions that groups need to consider

- Is there a bio-based alternative available on the market?
- Is the performance as good as that of similar products?
- Is there a suitable European standard for bio-based products?
- Have the environmental claims been certified?
- What is the minimum level of renewable content to call the product ‘bio-based?’
- How to compare recycled material with bio-based material?

It is through answering these questions across all participants in the manufacturing/application/use phases of a building that procurers will allow the increased use of sustainable materials.

1.4.2 Sustainable planning

The potential of bio-based building materials within the built environment offers an ideal way of improving sustainable construction and planning for properties, and particularly for affordable housing. In order to achieve such sustainable planning, there are two main methods of development—either a top-down approach or a bottom-up approach.

A top-down approach focusses on developing policies, strategies and standards. However, this approach was heavily accused. There is a view of this process being dependent on forcing the professional community to be aware of sustainable planning and design issues before responding or adapting them. The bottom-up approach is more informative as it aims at increasing awareness and knowledge among building professionals and then providing feedback to create a common understanding, a common language and a sense of responsibility towards the environment. More detailed evaluations of these methods to sustainable planning were presented by Salama and Alshuwikhat (2006), whilst Salama (2002) suggested it was important to use both methods to make critical assessments.

1.4.3 Embodied energy

According to statistics supplied by the EC Directorate-General of Energy, buildings are responsible for 40% of energy consumption and 36% of carbon emissions in the EU. As part of a commitment to reduce greenhouse gas emissions by 20% below 1990 levels, in 2010, the EC introduced the energy performance buildings directive (2010/31/EU), which states that all new buildings must be 'nearly zero-energy buildings' by 31 Dec. 2020 (public buildings by 31 Dec. 2018) and that EU countries must set minimum energy performance standards for new buildings. Under the energy efficiency directive (2012/27/EU), EU countries must draw up building renovation strategies under their national energy efficiency action plans. As the energy performance of buildings improves, more attention must be given to the EE and associated carbon emissions attributable to the building and building materials (Thormark, 2002; Sartori and Hestnes, 2007). Definitions of EE vary; some take the view that the EE of a building is the energy cost of its construction including the energy used to make the materials, whereas others include the energy associated with maintenance and in some cases disposal of the material as well. Since EE is estimated to be associated with 10% of total global carbon emissions of the building sector, it represents a significant factor (Lawrence, 2015). It is also important that comparisons between materials are made using the relevant functional unit. This can be a complicated analysis, since building elements can fulfil more than one function. For example, a wall element can provide support, separation, insulation, fire resistance, etc. For this reason, it is very unsatisfactory to make simple comparisons between materials on the basis of weight or volume (declared unit). It is also important that when different materials are compared, they have comparable system boundaries. For example, one study might measure the energy associated with the manufacture of a product only (e.g., cradle to factory gate), whereas another might also include delivery of that product to the building site. Although EE is an important parameter when it comes to choosing between materials, which have the same function in a building, it is also important to be aware of the partitioning between renewable and nonrenewable energy (which is not always reported).

The development of construction from using traditional, locally sourced materials to supplies obtained on a global scale has had major impacts upon the EE of materials.

In addition to this, the drive towards high-performance materials, particularly from nonrenewable resources, has led to considerable increases in energy inputs during the manufacturing phase. The use of bio-based (and renewable) construction materials can impart a beneficial effect on the EE associated with the construction of a building, since these renewable materials can have lower embodied energies than their nonrenewable counterparts. This means that the greenhouse gas emissions associated with the building materials can be reduced if renewable building materials are used.

In addition to benefits shown with EE, bio-based materials also sequester carbon from the environment, which is then encapsulated in the material until its eventual release. One study showing this is that with straw bale (Sutton and Black, 2011), as with all other plant-based construction materials, since carbon is stored during the growth of the plant and continues to be stored, whilst the material is used as a building material. At the end of its life, options for reuse or recycling can further extend the carbon storage. For example, it might be used as animal bedding (if cleaned of any other materials such as lime render). Alternatively, it can be ploughed back into the ground as soil conditioner. The same is true for bio-based coproducts, depending on the treatments applied to help extend the service life of a product, as has been demonstrated by the use of wood modification techniques for wood (Hill, 2006) and biocomposites (Fowler *et al.*, 2006). There is also the potential for incinerating a biogenic material at the end of life.

The sequestered carbon contributes significantly towards the overall EE calculated for a product. It is well recognised that the carbon within a bio-based product is kept in place within a construction throughout its service life, but the amount of carbon depends on the source of material and its density. For example, timber products can store up to 1 tonne of carbon dioxide per cubic metre of material used in a building, and this is further increased by a factor from energy saved in manufacture, again assumed to be 1 tonne per cubic metre (Van der Lugt, 2013). Similarly, the use of hemp fibres can contribute 325 kg carbon stored in a composite material during its service life, with an additional 22% achievable by impression of the degree of compression in manufacture (Pervais and Sain, 2003).

The role of carbon storage and its modelling within modern construction falls under the Product Environmental Footprint (*PEF*) as a form of biogenic carbon (i.e., its transformation from carbon dioxide to another product by photosynthesis). The Product Environmental Footprint Category Rules (*PEFCRs*) are still under development, and there is discussion as to the degree of effect from temporary or permanent carbon storage. As of Oct. 2016, the approach to carbon modelling outlined in the PEF guide excludes credits associated with temporary carbon storage or delayed emissions.

Carbon storage is considered permanent if the carbon is only expected to be emitted again more than three centuries after its uptake, whereas emissions expected to occur before that time (i.e., as a result of delayed emissions or temporary storage) are currently modelled as if emitted now. Based on this, there would appear to be a need to define these rules more accurately so that the benefits from the use of bio-based construction materials can be accurately measured, classified and inventoried.

1.4.4 Challenges to the use of bio-based building materials

As the construction industry changes to meet living environment requirements and increasing societal demands, greater opportunities for bio-based building materials should arise. However, these will be countered with increased marketing from nonrenewable and energy-intensive material sectors. In order to overcome such aggressive marketing, it is important to consider how to overcome some of the existing issues related to the use of bio-based materials in construction and in the wider global economy. Among the key issues affecting the development of the bio-based economy are

Political issues—National and international regulations continually change with different political agendas between countries and sometimes within a given country. It is important to focus on the major beneficial factors of any material within procurement strategies. Traditionally, there have been political inconsistencies when selecting materials and in particular bio-based materials. However, this is now being assisted by policies within Europe such as the green public procurement in Europe in 2006 (Bouwer *et al.*, 2006). This report focussed on the issue that there was often a lack of support at managerial level to the implementation of *GPP* preferences. Until recently, this reflects the lack of support and the need to continue to improve understanding of the performance of bio-based materials.

Social issues—As public perception changes, the social impact associated with bio-based materials alters. This is being enhanced by the implementation of life-cycle analyses and environmental product declarations. Through advances in processing, the performance of bio-based materials has been improved, with this being further enhanced through correct design. An additional social issue is the ever-increasing demand on global resources, which places greater strain on food security and land and water use. Opportunities that exist for bio-based materials remain after food sourcing, whilst the renewability of bio-based materials provides an additional benefit.

Environmental issues—This area overlaps considerably with social issues, in which the needs of the public mirror the environmental agendas being developed. These factors are complicated by the recognised need to maintain biodiversity and preservation of habitat, since deforestation, land-use change and biomass burning (particularly through slash and burn clearing) contribute to around 20% of the global carbon dioxide increases each year (IPCC, 2007). Factors related to minimising increases in global carbon dioxide levels are essential given the predicted effects of carbon dioxide equivalents rising above 550 ppm (Stern, 2006).

Economic issues—The greatest issue related to the implementation of bio-based materials is often the capital investment associated with startup projects. As with any new product or process, the scale of production often has additional implications on the market price per unit of a product when competing on established products from nonrenewable materials. Issues related to procurement can affect the uptake of more environmentally friendly products.

Legal issues—As of 4 Nov. 2016, the Paris agreement has come into force, representing the latest multinational agreement to try and curb climate change. Many countries not only are looking to better carbon dioxide equivalents released, often linked to implementing low energy construction alternatives, but also required energy per building. Further developments will need national and international ratification.

Table 1.6 ***SWOT*** **analysis for bio-based materials in construction**

Strengths	**Weaknesses**
• Ease of supply • Renewable • A recognised carbon storage option	• Production costs • Intrinsic natural properties impacting performance • Perceived low technology
Opportunities	**Threats**
• Readily modified to improve performance • Compatible with other materials • Significant reductions in energy • Increasing popularity with architects and designers	• Resource competition • Alternative land use (for food) • Aggressive marketing from established products • Changes in assessment criteria

Technological issues—As all the other issues come into force, one thing that links their effectiveness is the continued development of technological improvements. These improvements can be due to material availability and product design. A major factor in the availability of advanced materials is through changes in material supply, as exemplified by increased levels of genetically modified (*GM*) plants. Public perception of GM plants is not very high, and their effect on local habitats is still a matter of debate. Design is by far the largest area where technology can play a significant role for bio-based materials, as has been shown by the acceptance of cross-laminated timber (*CLT*) and 'massivholz' within modern construction, particularly for large, multistorey public buildings.

By comparing these technological issues, it is possible to develop a strength/weakness/opportunity/threat (SWOT analysis) for the use of bio-based materials in construction (Table 1.6). It can be seen that there are plenty of ways in which bio-based materials can play a major role in modern construction. However, competition from other materials and changes within developing legislature can affect the marketability of these products. Thus, it is important that the bio-based industry sectors maintain a strong, coordinated approach to the credentials of these products.

References

Amziane, A.S., Sonebi, M., 2016. Overview on bio-based building material made with plant aggregate. RILEM Techn. Lett. 1, 31–38.

Bouwer, M., Jonk, M., Berman, T., Bersani, R., Lusser, H., Nappa, V., et al., 2006. Green Public Procurement in Europe 2006—Conclusions and Recommendations. Virage Milieu & Management BV, Haarlem. http://europa.eu.int/comm/environment/gpp.

BREEAM, 2008. Information can be found at: http://www.breeam.org.

CEN, 2002a. EN 1990:2002. Eurocode: basis of structural design. European Committee for Standardization, Brussels, Belgium.

CEN, 2002b. EN 1991-1-1:2002. Eurocode 1: actions on structures. Part 1-1: General actions—densities, self-weight, imposed loads for buildings. European Committee for Standardization, Brussels, Belgium.

CEN, 2002c. EN 1991-1-2:2002. Eurocode 1: actions on structures. Part 1-2: general actions—actions on structures exposed to fire. European Committee for Standardization, Brussels, Belgium.
CEN, 2003a. EN 1991-2:2003. Eurocode 1: actions on structures. Part 2: traffic loads on bridges. European Committee for Standardization, Brussels, Belgium.
CEN, 2003b. EN 1991-1-3:2003. Eurocode 1: actions on structures. Part 1-3: general actions—snow loads. European Committee for Standardization, Brussels, Belgium.
CEN, 2003c. EN 1991-1-5:2003. Eurocode 1: actions on structures. Part 1–5: general actions—thermal actions. European Committee for Standardization, Brussels, Belgium.
CEN, 2004a. EN 1992-1-1:2004. Eurocode 2: design of concrete structures. Part 1-1: general rules and rules for buildings. European Committee for Standardization, Brussels, Belgium.
CEN, 2004b. EN 1992-1-2:2004. Eurocode 2: design of concrete structures. Part 1-2: general rules. structural fire design. European Committee for Standardization, Brussels, Belgium.
CEN, 2004c. EN 1994-1-1:2004. Eurocode 4: Design of composite steel and concrete structures—Part 1-1: general rules and rules for buildings. European Committee for Standardization, Brussels, Belgium.
CEN, 2004d. EN 1995-1-1:2004. Eurocode 5: design of timber structures. Part 1-1: general—common rules and rules for buildings. European Committee for Standardization, Brussels, Belgium.
CEN, 2004e. EN 1995-1-2:2004. Eurocode 5: design of timber structures. Part 1–2: general—structural fire design. European Committee for Standardization, Brussels, Belgium.
CEN, 2004f. EN 1995-2:2004. Eurocode 5: design of timber structures. Part 2: bridges. European Committee for Standardization, Brussels, Belgium.
CEN, 2004g. EN 1998-1:2004. Eurocode 8: design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings. European Committee for Standardization, Brussels, Belgium.
CEN, 2004h. EN 1998-5:2004. Eurocode 8: design of structures for earthquake resistance. Part 5: foundations, retaining structures and geotechnical aspects. European Committee for Standardization, Brussels, Belgium.
CEN, 2004i. EN 1998-6:2004. Eurocode 8: design of structures for earthquake resistance. Part 6: towers, masts and chimneys. European Committee for Standardization, Brussels, Belgium.
CEN, 2005a. EN 1991-1-4:2005. Eurocode 1: actions on structures. Part 1–4: general actions—wind actions. European Committee for Standardization, Brussels, Belgium.
CEN, 2005b. EN 1991-1-6:2005. Eurocode 1: actions on structures. Part 1–6: general actions—actions during execution. European Committee for Standardization, Brussels, Belgium.
CEN, 2005c. EN 1992-2:2005. Eurocode 2: design of concrete structures. concrete bridges. design and detailing rules. European Committee for Standardization, Brussels, Belgium.
CEN, 2005d. EN 1993-1-1:2005. Eurocode 3: design of steel structures. Part 1-1: general rules and rules for buildings. European Committee for Standardization, Brussels, Belgium.
CEN, 2005e. EN 1993-1-2:2005. Eurocode 3: design of steel structures. Part 1-2: general rules. structural fire design. European Committee for Standardization, Brussels, Belgium.
CEN, 2005f. EN 1993-1-8:2005. Eurocode 3: design of steel structures. Part 1-8: design of joints. European Committee for Standardization, Brussels, Belgium.
CEN, 2005g. EN 1993-1-9:2005. Eurocode 3: design of steel structures. Part 1-9: fatigue. European Committee for Standardization, Brussels, Belgium.
CEN, 2005h. EN 1993-1-10:2005. Eurocode 3: design of steel structures. Part 1-10: material toughness and through-thickness properties. European Committee for Standardization, Brussels, Belgium.

CEN, 2005i. EN 1994-1-2:2005. Eurocode 4: Design of composite steel and concrete structures—Part 1-2: general rules—structural fire design. European Committee for Standardization, Brussels, Belgium.
CEN, 2005j. EN 1994-2:2005. Eurocode 4: Design of composite steel and concrete structures—Part 2: general rules and rules for bridges. European Committee for Standardization, Brussels, Belgium.
CEN, 2005k. EN 1998-2:2005. Eurocode 8: design of structures for earthquake resistance. Part 2: bridges. European Committee for Standardization, Brussels, Belgium.
CEN, 2005l. EN 1998-3:2005. Eurocode 8: design of structures for earthquake resistance. Part 3: assessment and retrofitting of buildings. European Committee for Standardization, Brussels, Belgium.
CEN, 2006a. EN 1991-1-7:2006. Eurocode 1: actions on structures. Part 1–7: general actions—accidental actions. European Committee for Standardization, Brussels, Belgium.
CEN, 2006b. EN 1991-3:2006. Eurocode 1: actions on structures. Part 3: actions induced by cranes and machinery. European Committee for Standardization, Brussels, Belgium.
CEN, 2006c. EN 1991-4:2006. Eurocode 1: actions on structures. Part 4: silos and tanks. European Committee for Standardization, Brussels, Belgium.
CEN, 2006d. EN 1992-3:2006. Eurocode 2: design of concrete structures. liquid retaining and containing structures. European Committee for Standardization, Brussels, Belgium.
CEN, 2006e. EN 1993-1-3:2006. Eurocode 3: design of steel structures. Part 1-3: general rules. supplementary rules for cold-formed members and sheeting. European Committee for Standardization, Brussels, Belgium.
CEN, 2006f. EN 1993-1-4:2006. Eurocode 3: design of steel structures. Part 1-4: general rules. supplementary rules for stainless steels. European Committee for Standardization, Brussels, Belgium.
CEN, 2006g. EN 1993-1-5:2006. Eurocode 3: design of steel structures. Part 1-5: plated structural elements. European Committee for Standardization, Brussels, Belgium.
CEN, 2006h. EN 1993-1-11:2006. Eurocode 3: design of steel structures. Part 1-11: design of structures with tension components. European Committee for Standardization, Brussels, Belgium.
CEN, 2006i. EN 1993-2:2006. Eurocode 3: design of steel structures. Part 2: steel bridges. European Committee for Standardization, Brussels, Belgium.
CEN, 2006j. EN 1993-3-1:2006. Eurocode 3: design of steel structures. Part 3-1: towers, masts and chimneys. towers and masts. European Committee for Standardization, Brussels, Belgium.
CEN, 2006k. EN 1993-3-2:2006. Eurocode 3: design of steel structures. Part 3-2: towers, masts and chimneys. chimneys. European Committee for Standardization, Brussels, Belgium.
CEN, 2006l. EN 1998-4:2006. Eurocode 8: design of structures for earthquake resistance. Part 4: silos, tanks and pipelines. European Committee for Standardization, Brussels, Belgium.
CEN, 2007a. EN 1993-1-6:2007. Eurocode 3: design of steel structures. Part 1-6: strength and stability of shell structures. European Committee for Standardization, Brussels, Belgium.
CEN, 2007b. EN 1993-1-7:2007. Eurocode 3: design of steel structures. Part 1-7: plated structures subject to out of plane loading. European Committee for Standardization, Brussels, Belgium.
CEN, 2007c. EN 1993-1-12:2007. Eurocode 3: design of steel structures. Part 1-12: additional rules for the extension of EN 1993 up to steel grades S 700. European Committee for Standardization, Brussels, Belgium.
CEN, 2007d. EN 1993-4-1:2007. Eurocode 3: design of steel structures. Part 4-1: silos. European Committee for Standardization, Brussels, Belgium.

CEN, 2007e. EN 1993-4-2:2007. Eurocode 3: design of steel structures. Part 4-2: tanks. European Committee for Standardization, Brussels, Belgium.
CEN, 2007f. EN 1993-4-3:2007. Eurocode 3: design of steel structures. Part 4-3: pipelines. European Committee for Standardization, Brussels, Belgium.
CEN, 2007g. EN 1993-5:2007. Eurocode 3: design of steel structures. Part 5: piling. European Committee for Standardization, Brussels, Belgium.
CEN, 2007h. EN 1993-6:2007. Eurocode 3: design of steel structures. Part 6: crane supporting structures. European Committee for Standardization, Brussels, Belgium.
Crawley, D., Aho, I., 1999. Building environmental assessment methods: applications and development trends. Build. Res. Inf. 27, 300–308.
Emission Commission, 2011. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 'A Roadmap for moving to a competitive low carbon economy in 2050' (COM(2011) 112). http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52011DC0112.
European Commission, 2003. Council Directive 2002/91/EC of 16 December 2002 on the energy performance of buildings. Off. J. Eur. Communities 65–71. No L 1 of 04/01/2003.
European Commission, 2009. Lead market initiative for Europe mid-term progress report. SEC (2009) 1198 final. http://register.consilium.europa.eu/doc/srv?l=EN&f=ST%2012959%202009%20INIT.
European Commission, 2012. Innovating for Sustainable Growth. A Bioeconomy for Europe. European Commission, Brussels, ISBN: 978-92-79-25376-8. http://dx.doi.org/10.2777/6462.
European Commission, 2016. The European Construction Sector. A Global Partner. http://ec.europa.eu/growth/sectors/construction/index_en.htm.
Fan, M., Fu, F., 2016. Advanced High Strength Natural Fibre Composites in Construction. Woodhead Publishing Series in Composite Science and Engineering. Woodhead Publishing, London, ISBN: 978-0-08-100411-1, 577 p.
Fowler, P.A., Hughes, J.M., Elias, R.M., 2006. Biocomposites: technology, environmental credentials and market forces. J. Sci. Food Agric. 86, 1781–1789.
Hill, C.A.S., 2006. Wood Modification, Chemical, Thermal and Other Processes. John Wiley & Sons, New York, NY, ISBN: 978-0-470-02172-9.
IEA—International Energy Agency, 2011. Energy technology perspectives 2010 findings. In: Grantham Institute/International Energy Agency Workshop: The Reduction of Global Carbon Emissions in the Building Sector to 2050. Grantham Institute for Climate Change, London.
IPCC—Intergovernmental Panel on Climate Change, 2007. IPCC Fourth Assessment Report: Climate Change 2007. Cambridge University Press, Cambridge.
ITE Build and Interiors, 2015. India to be a 'new engine' of global construction growth to 2030—report. http://www.buildingshows.com/market-insights/india-indonesia/india-to-be-a-new-engine-of-global-construction-growth-to-2030-report/801805481.
Jones, D., Ormondroyd, G., Lawther, M., Tweed, C., 2011. Wood composites in modern methods of construction: applications and environmental considerations. In: Proc. International Panel Products Symposium. BioComposites Centre, Bangor, UK, pp. 197–202.
Lawrence, M., 2015. Reducing the environmental impact of construction by using renewable materials. J. Renew. Mater. 3 (3), 163–174.
Magniont, C., 2010. Contribution à la Formulation et à la Caractérisation d'un Écomatériau de Construction à Base d'Agroressources (PhD thesis). Toulouse.
Matos, G., Wagner, L., 1998. Consumption of materials in the United States, 1900-1995. Annu. Rev. Energy Environ. 23, 107–122.

OJEU, 2011. Regulation (EU) 30572011. Laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:088:0005:0043:EN:PDF.

Pedro, J.B., Meijer, F., Visscher, H., 2010. Technical building regulations in EU countries presentation: comparison of their organization and formulation. In: 18th CIB (International Council for Research and Innovation in Building and Construction) World Congress: W113—Special Track CIB W113—Law and Dispute Resolution. CIB Publication 345, CIB General Secretary, Rotterdam, The Netherlands, pp. 38–50.

Pervais, M., Sain, M., 2003. Carbon storage potential in natural fiber composites. Resour. Conserv. Recycl. 39 (4), 325–340.

Peuportier, B., 2008. Eco-conception des bâtiments et des quartiers. Presses de l'Ecole des Mines, Paris.

Salama, A., 2002. Sustainability: a dream, utopia, or romantic gesture. IAPS Bull. 21, 21–23.

Salama, A.M., Alshuwikhat, H., 2006. A trans-disciplinary approach for a comprehensive understanding of sustainable affordable housing. Glob. Built Environ. Rev. 5 (3), 35–50.

Sartori, I., Hestnes, A., 2007. Energy use in the life cycle of conventional and low energy buildings: a review article. Energ. Buildings 39, 249–257. http://dx.doi.org/10.1016/j.enbuild.2006.07.001.

Stern, N., 2006. Stern review on the economics of climate change. HM treasury independent reviews, UK. http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/sternreview_index.htm.

Sutton, A., Black, D., 2011. Straw Bale. An introduction to low-impact building materials. BRE Information Paper IP15/11 IHS. BRE Press, Watford. ISBN: 978-1-84806-226-9.

Thormark, C., 2002. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Build. Environ. 37, 429–435.

UK Govt, 2013. Construction 2025. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/210099/bis-13-955-construction-2025-industrial-strategy.pdf.

UNEP SBCI, 2009. Buildings and Climate Change: Summary for Decision-Makers. UNEP DTIE, Paris.

Van der Lugt, P., 2013. Carbon Storage Utilising Timber Products. https://www.accoya.com/wp-content/uploads/2013/09/Carbon-Storage-using-Timber-Products.pdf.

Wackernagel, M., Schulz, N.B., Deumling, D., Callejas Linares, A., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J., 2002. Tracking the ecological overshoot of the human economy. Proc. Natl. Acad. Sci. 99 (14), 9266–9271.

This page intentionally left blank

Wood as bio-based building material

2

2.1 Introduction

C.-M. Popescu
Petru Poni Institute of Macromolecular Chemistry of the Romanian Academy, Iasi, Romania

Wood has played an important role in human activity over the centuries. Since ancient times, one of the first major innovations of humankind was using wood for fire, cooking and heating. Due to its versatility, the use of wood was expanded for agricultural implements and tools, shelters and houses, bridges, road surfaces, ships and boats, arrows and bows, spears, shoes, wheelbarrows, waggons, ladders and so on. Since the industrial revolution, the use of wood in houses, bridges and other construction structures has reduced due to the development of other materials like concrete, bricks or steel.

Over the past decade, in the course of current global challenges with respect to carbon dioxide emissions and climate change, the concept of green building has become more mainstream, and the public is becoming aware of the potential environmental benefits of alternatives to conventional construction. Therefore, the reapplication of wood and wood-based products as a renewable resource used in construction and architectural coating materials is highly contemporary.

At the same time, the focus of green building is on reducing energy consumption during construction and in use (such as better insulation, more efficient appliances and heating, ventilation and air-conditioning systems) and reducing negative human health impacts (such as controlled ventilation and humidity).

Additionally, low costs, aesthetics, artistic and design requirements or tradition and nature-based inspiration, easy accessibility and relatively simple processing contribute to the increasing popularity of wood.

This chapter presents a brief description of the structure of solid wood and the manufacture of wood-based products (such as cross laminated timber (*CLT*), panel products, wood-plastic composites (*WPCs*) and cellulose and paper), their properties and possible applications as bio-based building materials.

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00002-1
© 2017 Elsevier Ltd. All rights reserved.

2.2 Solid wood

B. Mazela, C.-M. Popescu†*
*Poznan University of Life Sciences, Poznan, Poland
†Petru Poni Institute of Macromolecular Chemistry of the Romanian Academy, Iasi, Romania

Wood has been known and used as a renewable raw and engineering material for thousands of years and is still nowadays an essential building material due to its qualities such as light weight, processability, good mechanical properties, sustainability, aesthetic appearance and technological applicability (used for wood processing in craftsmanship and industrial practise; Rowell, 2005; Fengel and Wegener, 1989; Hill, 2006; Ermeydan *et al.*, 2014). Wood is also suitable for energetic recovery at the end of its service life, after ideally long-lasting carbon storage in a high-value application (Rowell, 2005; Fengel and Wegener, 1989; Hill, 2006). Moreover, wood can be treated to resist decay, and with proper construction techniques and coatings, wood buildings can last hundreds of years. Today, wood still has a significant impact because of its sustainability, with increasing utilisation as tools, paper, buildings, bridges, guard rails, rail road ties, posts, poles, mulches, furniture, and packaging.

2.2.1 Structure of wood

Wood is a complex composite material, built up of compounds connected with each other by different chemical and/or physical bonds. The quality and quantity of these compounds vary between species, between trees and within the tree itself (Rowell, 2005; Hill, 2006).

To understand the structure of wood, several levels should be considered, that is, macro, submacro, micro, submicro and molecular level (Nilsson and Rowell, 2012).

In brief, at the macrolevel of a tree, wood can be divided in two classes: *softwoods*—the wood that comes from gymnosperms (mostly conifers) and *hardwoods*—the wood that comes from angiosperms (deciduous trees). They also differ in terms of their component cells. The structure of softwood is relatively simple. The axial or vertical system is composed mostly of axial tracheids, and the radial or horizontal system is composed mostly of ray parenchyma cells. The structure of hardwoods is more complex, being composed of fibrous elements, vessel elements and axial parenchyma cells (Wiedenhoeft and Miller, 2005), as shown in Fig. 2.1.

The traditional terms, hardwood and softwood, have no accurate reference to the relative hardness and softness of the wood and should therefore be interpreted simply as designations for the two major botanical groups they represent.

Wood in the tree is divided into two zones—*sapwood* and *heartwood*. The first one consists of the actively conducting portion of the stem under the bark and phloem, in which parenchyma cells are still alive and metabolically active, whilst the second one is the region of non-active cells at the core of the tree, which has the function of the long-term storage of biochemicals. Typically, the more leaves a tree bears and the more vigorous its

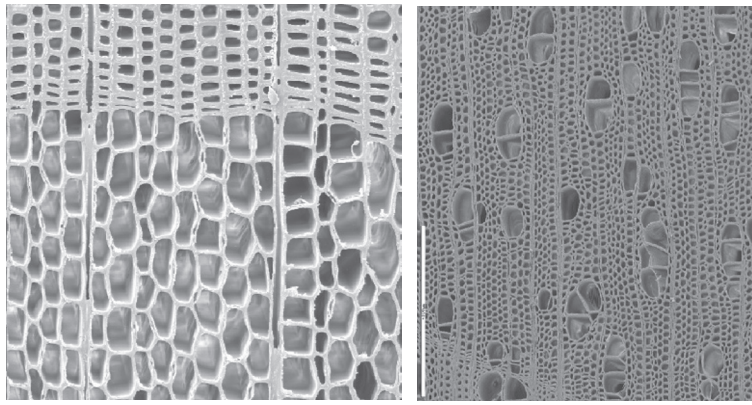


Fig. 2.1 (A) *SEM* image of softwood (Fir (*Abies* sp.)) and (B) hardwood (Birch (*Betula* sp.)). (B) Courtesy and with permission of Dr Michael Hale.

growth is, the larger is the volume of sapwood produced. Depending on the wood species, sometimes, there is no visible difference between the two zones in the wood.

Going down to the microlevel, *annual rings* or *growth rings* can be differentiated. The width of annual rings depends on the type of tree (genetic conditions), along with its age, climatic conditions, habitat, lighting, precipitation, air temperature, etc. Trees belonging to fast-growing species (e.g. poplars and willows) form wide rings, whilst slow-growing species (e.g. yew) form narrow rings even in the most favourable conditions. The width of the annual rings changes also along the height and radius of the tree. These also contain two zones—earlywood (springwood) and latewood (summerwood) (Wiedenhoeft and Miller, 2005). There are three fundamental patterns within a growth ring: no change in cell pattern across the ring, a gradual reduction of the inner diameter of conducting elements from the earlywood to the latewood and a sudden and distinct change in the inner diameter of the conducting elements across the ring (Wiedenhoeft and Miller, 2005; Fengel and Wegener, 1989).

The most pronounced annual rings can be found in softwoods (due to a significant difference between the early and latewood colours). Annual rings are equally pronounced in the wood of porous hardwood species, whilst in the case of diffuse-porous hardwoods, the boundaries of annual rings are less pronounced and sometimes hard to be observed.

A growth ring is composed of two primary domains, the protoplast and the cell wall. The first one is a sum of the living contents that are bounded by the cell membrane, whilst the second one is a non-living, largely carbohydrate matrix extruded by the protoplast to the exterior of the cell membrane (Raven *et al.*, 1999).

The *cell wall* is a highly regular structure, from one cell type to another, between species and even when comparing softwoods with hardwoods. It consists of three main regions: the middle lamella, the primary wall and the secondary wall (Wiedenhoeft and Miller, 2005).

The primary *structural compounds* of the cell wall are *cellulose* (the building material of the elements of cell walls), *hemicelluloses* (i.e. hexosans and pentosans) and *lignin*. All these compounds are more or less permanently bonded between them and fill

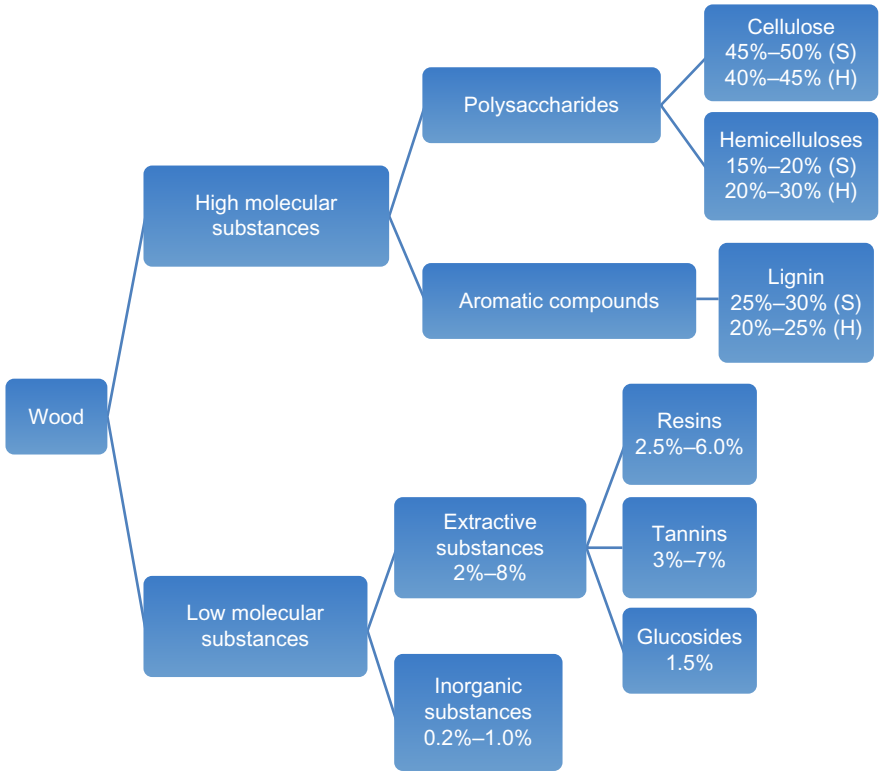


Fig. 2.2 Chemical composition of wood (S—softwoods and H—hardwoods).

the interfibrillar spaces of cell walls. Small amounts of other polymeric compounds, such as starch, pectins, resins and proteins or other non-polymeric compounds, may also be present in wood, constituting a group of extractive substances. The average percentage of the wood chemical compounds is shown in Fig. 2.2.

Cellulose is one of the most important structural components of cell walls, being of about 40–50 wt% content (Fengel and Wegener, 1989). It is a linear homopolymer built up of monomeric units of β-D-glucopyranose. The chemical formula for cellulose is $(C_6H_{10}O_5)_n$, where n is its degree of polymerisation (DP). In the case of wood, cellulose has a DP of about 10,000. Glucose residues, which are the basic structural units of cellulose, contain three alcohol hydroxyl groups, which largely determine the degree of chemical reactivity and the sorption phenomena (Saka, 2001). Detailed information about the cellulose structure and properties is given in Section 2.6 of this chapter.

Contrary to cellulose, hemicelluloses form branched carbohydrate copolymers built up of different heteroglycan sugar units [like D-glucose, D-xylose, D-mannose, D-galactose, L-arabinose, L-rhamnose, 4-*O*-methyl-D-glucuronic acid, D-glucuronic acid and D-galacturonic acid (Fig. 2.3)] depending upon the species from which they are obtained (i.e. hardwood or softwood) and consist of short side chains attached to the backbone units. Their quantity in wood structure ranges from 15 to 30 wt%. Molecular mass of hemicelluloses is much lower than that of cellulose, and they have a degree of polymerisation (DP) ranging from 200 to 300 (Crawford and Crawford, 1980; Saka, 2001; Fengel and Wegener, 1989).

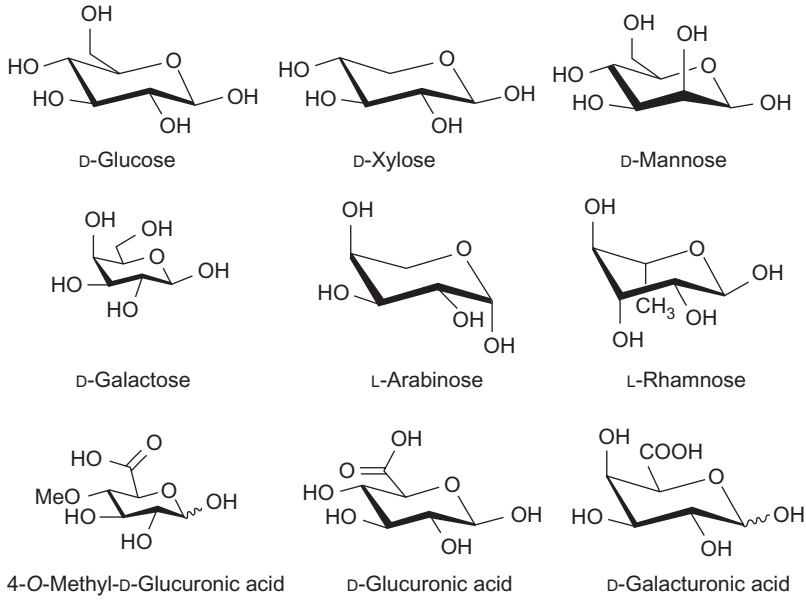


Fig. 2.3 Monomeric units in hemicelluloses.

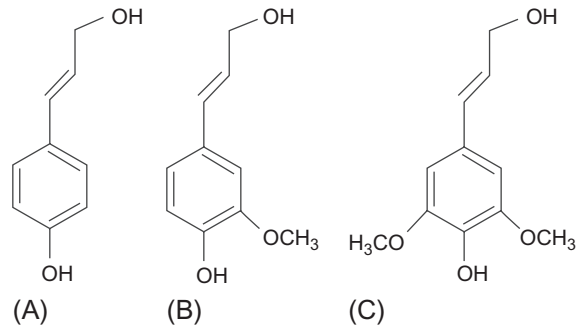


Fig. 2.4 Phenylpropane units: (A) *p*-hydroxyphenyl (H), (B) guaiacyl (G) and (C) syringyl (S).

Due to their amorphous nature hemicelluloses contain the greatest part of available hydroxyl groups in the cell wall, reacting easily and being thermally less stable than cellulose or lignin. Hemicelluloses act like interfacial coupling agents between the highly polar surface of microfibrils and much less polar lignin substance, forming hydrogen bonds on the surface of microfibrils and covalent bonds with lignin substance (Rowell *et al.*, 2005).

Lignin is an important component of wood accounting for 25–30 wt% of its total mass. It is a complex three-dimensional polymer in its native state, and it is amorphous. It consists mainly of phenylpropane—guaiacyl (G), syringyl (S) and *p*-hydroxyphenyl (H) (Fig. 2.4)—units linked together by aryl ether (involving C4) interunit linkages and carbon–carbon bonds (Agarwal and Atall, 2010; Dence and Lin, 1992; Fengel and Wegener, 1989). Most often, the molecular mass of lignin is ~11,000 and its DP ~60.

Lignin not only is present primarily in the middle lamella but also fills the interfibrillar spaces in individual layers of cell walls.

The *extractive substances* (aromatic and aliphatic chemical components of natural resins, tannins, dyes, lignans, glucosides, terpenes, alcohols, fats and waxes) and *mineral substances* have relatively low molecular masses (Fengel and Wegener, 1989). They are classified as so-called non-structural substances because they do not form structural elements within the cell walls and have no significant influence on mechanical properties of wood. Resinous and fat substances, waxes and most phenol compounds may be extracted using organic solvents, whilst tannins, dyes, pectins and vegetal rubbers dissolve easily in water. Depending on the wood species, the content of extractive substances ranges from 2% to 8%. The extractive components include also mineral substances determined in the form of ash, and their content does not exceed 1% of total mass of wood (Fengel and Wegener, 1989).

2.2.1.1 Elemental composition

Wood is a material built up mainly from carbon, hydrogen and oxygen. The insignificant amounts of protein compounds containing nitrogen can be a nutrient for numerous living wood-destroying organisms. The average elemental composition of dry wood is presented in Table 2.1.

Apart from the main components, wood also contains simple and complex inorganic substances such as calcium, potassium, magnesium, manganese, sodium, aluminium, iron, carbonates, chlorates, phosphates and sulphates. In terms of elemental composition, no differences between softwood and hardwood or between individual wood species are observed.

2.2.2 Wood properties

Physical properties of wood describe the quantitative characteristics of wood and its behaviour to external influences other than applied forces. Amongst these are appearance, smell, morphology, roughness, smoothness, specific surface area, sorption and permeability, density, dimensional stability, thermal properties, and acoustic and electric properties, natural durability and chemical resistance. These properties can significantly influence the performance and strength of wood used in structural applications.

Table 2.1 Elemental composition of wood

Component	Content (wt%)
Carbon	49–51
Oxygen	43–44
Hydrogen	6–7
Nitrogen	0.1–0.3
Ash	0.2–0.6

2.2.2.1 Wood appearance

The *wood colour*, pattern and gloss are important criteria for the aesthetic assessment of wood and final wood products.

Wood colour—this depends on the wood species and many external factors but mainly on climatic conditions. The European tree species are divided in six major colours: *light-brown colour* (fir, spruce, birch, aspen, hornbeam, beech and sycamore), *yellow colour* (birch, Swiss pine and alder), *brown colour* (oak, elm, ash, juniper and willow), *reddish colour* (larch, pine, cherry, sweet cherry and plum), *greenish colour* (locust) and *dark colour* (walnut). The wood of trees growing in subtropical forests is characterised by the broadest range of colours (virtually all colours, excluding blue), whilst wood colour from tropical trees ranges from yellow (satinwood), to red (pernambuco) and purple (amaranth), to black (ebony).

The colour of wood changes significantly (darkens) with time, due to the exposure to light and oxidising action of the air. At the same time, the surface colour of wood exposed to atmospheric factors turns grey, due to partial leaching of chemical compounds, which are not integral part of cell structures, or changes due to the fungi action or the reaction of tannins present in wood with water.

Wood gloss—depends on the wood species, anatomical section and especially on the type of machining and surface finishing. The gloss of unfinished natural wood is hardly visible. More intense gloss can be visible on the radial sections of hardwood species, which have broad and high tree rays. In such cases, the tree rays are taken as glossy streaks called silver grains (e.g. oak, elm, beech and plane tree).

Wood pattern—is a property closely connected with its structure (species) and the type of anatomical section and it also depends on the width of annual rings, amount of latewood, size of tree rays and on the quantity, size and form of knots and their location.

The changes in wood appearance due to different factors affect the aesthetic performance of wood, especially when this is used for cladding and floors.

2.2.2.2 Density of wood

Wood density is an important property in the construction sector. The relation of the mass of a sample to its volume is the basic and most important physical quantity connected with wood. In the case of wood, there are two different types of densities that can be determined: the density of wood substance and wood cell walls and wood conventional density. Due to the fact that the first one is almost constant for all wood species (~1.5 g/m^3) (Huang *et al.*, 2003), in practise, wood density is determined by its porosity and moisture content. The wood conventional density values depend mainly on the tree species (wood structure), the location of wood in the trunk and its moisture content. Wood of the main species of the temperate climate zones is characterised by density within the range from 350 (white pine—*Pinus strobus* L.) to 800 kg/m^3 (hornbeam—*Carpinus betulus* L.).

Within each tree species, wood density also depends on the width of the annual rings, the amount of latewood and the location of wood in the tree trunk. For softwood species, the decrease of the annual ring width induces the increase of density to a maximum value (at approximately 1 mm tree ring width) and then drops significantly

with further decrease in the width of the annual rings. For ring-porous hardwood species, the increase in the width of annual rings is accompanied by an increase in wood density to the maximum value, which usually stays constant. In the case of wood of diffuse-porous species, no dependence between wood density and width of annual rings is observed (Fengel and Wegener, 1989).

Based on the density values, there are several groups:

- Very heavy wood (density > 800 kg/m^3), hornbeam (*Carpinus betulus* L.), yew (*Taxus* sp.), box (*Boxus* sp.), ebony (*Diospyros* sp.) and eucalyptus (*Eucalyptus* sp.).
- Heavy wood (density of 710–800 kg/m^3), locust (*Robinia pseudoacacia*), beech (*Fagus* sp.), oak (*Quercus robur*), walnut (*Juglans regia*), pear (*Pyrus* sp.) and plum (*Prunus* sp.).
- Moderately heavy wood (density of 610–700 kg/m^3), birch (*Betula* sp.), maple (*Acer* sp.), sycamore (*Platanus occidentalis*) and larch (*Larix* sp.).
- Light wood (density of 510–600 kg/m^3), juniper (*Juniperus* sp.), horse chestnut (*Aesculus hippocastanum*) and mahogany (*Swietenia* sp.).
- Moderately light wood (density of 410–500 kg/m^3), pine (*Pinus* sp.), spruce (*Picea* sp.), fir (*Abies* sp.), alder (*Alnus* sp.), lime (*Tilia* sp.), aspen (*Populus tremula*), cypress (*Cupressus* sp.), cedar (*Cedrus* sp.) and teak (*Tectona grandis*).
- Very light wood (density < 400 kg/m^3), poplar (*Populus* sp.), white pine (*Pinus strobus*) and balsa (*Ochroma pyramidale*).

Porosity of wood is an important parameter that influences significantly not only the material properties such as flow, permeability, adsorption and impregnability but also thermal conductivity and tensile and bending strength (Plötze and Niemz, 2011; Ding *et al.*, 2008). It is defined by the relation of volume of pores contained in the wood to its volume or unity from which is subtracted the solid-volume fraction. Wood porosity depends on its density; therefore, the higher the wood density, the lower the wood porosity.

2.2.2.3 Water sorption and permeability

Wood is a hygroscopic material; it can adsorb and/or desorb water from the surrounding environment, tending to reach an equilibrium condition when the atmospheric relative humidity (*RH*) is stable. Therefore, the *moisture content* (*MC*) of wood is the relative content of water present in the wood tissue, which results from natural condition (in living tree) or is a result of the action of atmospheric or exploitation factors that affect the material for a longer period. The relationship between the equilibrium moisture content and RH at constant temperature is known as a sorption isotherm. The sorption isotherm is a characteristic of the material but is influenced by the temperature and previous sorption history of the sample under examination. Under unstable environmental RH conditions, the wood moisture is changing continuously, and equilibrium is rarely reached (Popescu and Hill, 2013; Engelund *et al.*, 2013).

In a living tree, the moisture content values vary between tree species, within the tree, for example between sapwood and heartwood; between seasons; and possibly also with the time of the day. For softwoods, the moisture content of heartwood is typically considerably lower than for sapwood (Pallardy and Kozlowski, 2008; Engelund *et al.*, 2013). This is not always the case for hardwoods, for which the relation between moisture content in heartwood and sapwood depends on species and may also depend on season (Pallardy and Kozlowski, 2008; Engelund *et al.*, 2013).

It has been mentioned that the water in wood may be present in three different states (free water, freezing bound water and non-freezing bound water; Nakamura *et al.*, 1981; Berthold *et al.*, 1996). Free water is considered to be the capillary water within the cell lumens, whilst the bound water interacts with the more or less hydrophilic wood polymers. Freezing bound water has been assumed to be moderately bound to the cell wall, whilst the non-freezing is strongly bound water.

Considering that the hydroxyl groups of the wood polymers are the main sorption sites, at low-moisture content, it is suggested that water molecules may bind to two neighbouring hydroxyl groups simultaneously (Joly *et al.*, 1996) forming the monolayer or strongly bound water to polar groups within the cell wall. This takes place at a moisture content of up to ~4%. Further, polymolecular adsorption takes place in the range of a moisture content ranging from ~4% to 12%, forming multilayer or weakly bound water to the substrate or in the larger water clusters. The phenomenon of capillary sorption encompasses wood moisture content from 12% to ~30% (cell wall saturation point). The moisture saturation point is achieved by wood when it is kept long enough in an environment with a maximum RH percentage and is a quantity independent of the wood species.

The measurement of the moisture content provides information on the current state of wood moistening in given environmental conditions (see Fig. 2.5).

Moisture content is typically expressed as a percentage of the wood mass. Therefore, at the same moisture content, the mass of water contained in wood is a different value for individual wood species. Wood of higher density contains more water than wood of lower density at the same moisture content.

Adsorption and desorption of water is accompanied by changes in the wood linear dimensions (swelling and shrinkage, respectively). Due to the anisotropic anatomy of wood, its moisture content-related deformations are different for the longitudinal, radial and tangential directions. The largest size change takes place in the direction of the annual growth rings (tangentially), less crosswise to the rings and little in direction of the stem. In addition, different wood types swell differently (Rowell, 2005; Hohne and Tauer, 2016).

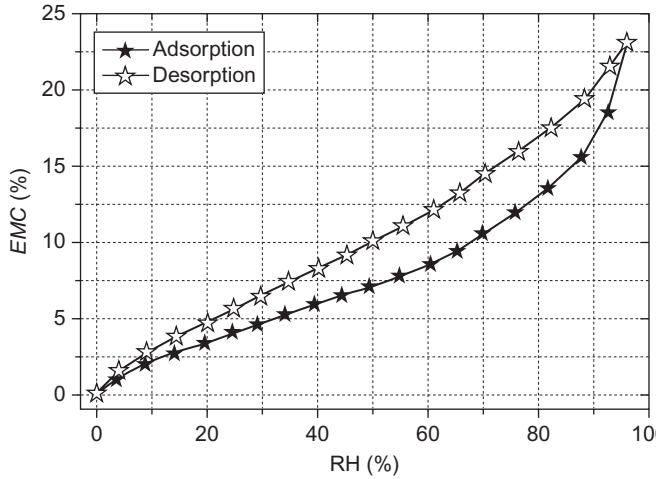


Fig. 2.5 Sorption isotherm plotted as a function of sample relative humidity for birch (*Betula* sp.) wood.

Wood absorbability is the ability of wood immersed in water (or other liquids) to absorb it. Absorption is defined by three parameters, velocity of absorption, maximum water capacity and degree (coefficient) of saturation. Their numerical values depend on the wood species (its density and porosity), the trunk zone (sapwood or heartwood), the initial moisture content of wood tissue, the type of liquid, the size of the sample and the anatomical direction of wood.

Wood permeability is the susceptibility of the material to moistening and its ability to allow the liquid pass through it. This property is important, amongst others, for impregnation processes (in wood preservation) and construction. The main factors determining the susceptibility to permeation include the wood anatomy, the trunk cross section zone (sapwood, heartwood), the anatomical direction and the pressure of the liquid.

The penetration of water, when wood is exposed to humidity, and the rate of release, when wood is allowed to dry, have a significant influence on determining the performance and expected service life. Because permeability to water is one of the key factors affecting the performance of a wooden component as it controls the possibility of fungal decay, the wood species that are less permeable to water are expected to perform better than permeable species in use classes where wood is exposed to intermittent wetting. Time of wetness is also a key factor for fungal development, and it is affected by environmental parameters, including design, building physics and exposure and maintenance, which have a remarkable effect on performance and vary greatly across Europe (Kutnik *et al.*, 2014).

Thermal properties of wood characterise the behaviour of wood under thermal load, when the temperature increases or decreases. The temperature is an important parameter, which influences different technological processes and specific properties of wood. Amongst many thermal properties of structural materials, the following are the most important within the wood technology sector, specific heat, thermal conductivity and thermal expansion (Czajkowski *et al.*, 2016).

Specific heat (specific heat capacity) of a material is defined as the amount of heat per unit mass of the material required to raise its temperature by 1°C and characterises material in terms of its ability to accumulate heat. It is considered that the specific heat of wood is high; therefore, with the same amount of heat provided, its temperature rises slower than the temperatures of metal or glass. The specific heat of wood affects its insulating properties and heat capacity (Czajkowski *et al.*, 2016; Glass and Zelinka, 2010).

Specific thermal conductivity of a given material is its ability to conduct heat from places of higher temperature to places of lower temperature by passing the flow of radiant energy to adjacent molecules. This material property is described by numerical value of the thermal conductivity coefficient and the higher its value, the more heat is conducted by the material. Thermal conductivity of wood rises with increasing moisture content and density. It also depends on the wood temperature and the direction of the heat current flow in relation to the direction of the grain. Measured along the grain, the thermal conductivity coefficient of wood is twice as high as measured in the direction transverse to the grain, that is, 0.35 and 0.15 W/mK, respectively (Czajkowski *et al.*, 2016; Glass and Zelinka, 2010).

Thermal diffusivity is a measure of how quickly a material can absorb heat from its surroundings. It is defined as the ratio of thermal conductivity to the product of density and heat capacity. Because of the low thermal conductivity and moderate density and heat capacity of wood, the thermal diffusivity of wood is much lower than that of other structural materials, such as metal, brick and stone (Glass and Zelinka, 2010).

Thermal expansion of wood is a property that appears due to the increase of temperature (heating). It is characterised by the coefficient of linear and volumetric expansion. The first one is the relation of lengthening of a given material unit length per material temperature increase to its initial length, whilst the second one is calculated analogically. At the same time, the linear expansion calculated on longitudinal direction is much lower than the radial or tangential ones. A low longitudinal expansion coefficient is an advantage of wood used in building structures (Glass and Zelinka, 2010).

Acoustic properties of wood are a group of features connected with the course of phenomena accompanying the travelling of ultrasonic waves and their influence on other physical parameters of wood. The anatomy of wood allows sound to travel in the directions parallel and transverse to the grain. Hence, determination of each property of wood is carried out in three anatomical planes (directions) (Bucur, 2006). The ultrasonic wave velocity in wood is also affected by different factors. Changes in the growth ring, natural defects, moisture and temperature will cause attenuation of the acoustic ultrasonic parameters. For example, the speed decreases when the moisture content is higher in the radial direction than that in the tangential direction. Acoustic properties are also influenced by the density of the material (Chen *et al.*, 2012; Yang *et al.*, 2015).

2.2.2.4 Mechanical properties of wood

Mechanical properties are the most important properties of wood as a structural material. They define the material's ability to resist deformation and distortion (elastic properties) or failure (strength properties) and its ability to become deformed in an elastic and plastic way as a result of the action of external mechanical forces.

Wood mechanical properties are controlled by its physical and anatomical characteristics, like wood density, grain angle, tracheid length and microfibril angle of the S2 layer in the cell wall (Zhang, 1995). They also can be altered by different environmental factors. Therefore, the changes in pH, moisture and temperature; the influence of decay, fire and UV radiation; and the adsorption of chemicals from the environment can have a significant effect on strength properties. The susceptibility of wood to strength loss and the magnitude of degradation are directly related to the severity of the thermal, chemical and/or biochemical environment exposure (Winandy and Rowell, 2005). Due to the heterogeneous anatomy of wood tissue, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes, longitudinal (parallel to the fibre/grain), radial (normal to the growth rings/perpendicular to the grain in the radial direction) and tangential (perpendicular to the grain but tangent to the growth rings).

Two parameters are related to the mechanical properties of wood, stress and strain. *Stress* is a measure of the internal forces exerted in a material as a result of an

application of an external force (i.e. load). There are three types of primary stress: tensile stress (pulls or elongates an object), compressive stress (pushes or compresses an object) and shear stress. Bending stress is a combination of all three of the primary stresses and causes rotational distortion or flexure in an object.

Strain is the measure of a material's ability to deform (elongate, compress or rotate) under stress.

The above-mentioned parameters involve two moduli:

- Modulus of elasticity that describes the relationship of load (stress) to axial deformation (strain). Elasticity implies that deformations produced by low stress are completely recoverable after loads are removed. When loaded to higher stress levels, plastic deformation or failure occurs. The elastic ratios and the elastic constants themselves vary within and between species and with moisture content and specific gravity (Kretschmann, 2010).
- Modulus of rigidity (*MOR*) or shear modulus that describes the internal distribution of shearing stress to shear strain or, more precisely, angular (i.e. rotational) displacement within a material. As with moduli of elasticity, the moduli of rigidity vary within and between species and with moisture content and specific gravity (Kretschmann, 2010).

Mechanical properties of wood measured and represented as 'strength properties' include modulus of rupture in bending, maximum stress in compression parallel to grain, compressive stress perpendicular to grain and shear strength parallel to grain. Additional measurements are often made to evaluate work to maximum load in bending, impact bending strength, tensile strength perpendicular to grain and hardness (Kretschmann, 2010).

2.2.3 Wood treatments

In order to improve some of the wood properties (i.e. dimensional stability, resistance to biological degradation, thermal stability or fire resistance, UV resistance and mechanical properties), the application of different treatment is an important procedure before timber is used in the construction sector (Rowell, 2007; Hill, 2006).

Several available wood treatments induce modifications in wood structure, which have an effect by *reducing the water sorption* in order to minimise changes in wood volume and inhibit the growth of fungi and bacteria (which can be realised by hydrophobic treatment or filling with blocking agents); *quenching chemically active groups* such as hydroxyl groups in order to prevent the attack by fungi, bacteria and insects and also increase fire resistance to some extent; *impregnating preservatives* to kill fungi, bacteria and insects directly or impregnating fire retardant for thermal stability and *coating moisture-*, *bio-*, *fire- or UV-resistant agents* on the surface of wood (Ramage *et al.*, 2017).

Therefore, wood treatments involve the modification of the cell wall, impregnation or coating. The first one is further divided into thermal modification and chemical modification.

Thermal modification, with a large applicability in industry, is an effective way to improve wood dimensional stability and durability against biodegradation (Hillis and Rozsa, 1985; Hill, 2006). During thermal treatment, chemical modifications of the wood components take place, and low molecular compounds are released from

the hydrolysis of acetyl esters in xylan (Esteves and Pereira, 2009). Hemicelluloses are depolymerised into oligomeric and monomeric units and further dehydrated to aldehydes under acidic conditions, leading to fewer hydroxyl groups and less hygroscopic. The other two main components of wood, cellulose and lignin are less affected during thermal treatments. However, the softening of lignin and formation of lignin derivatives can increase the degree of cross-linking in the cell wall; this results in the decrease of the elastic properties of treated timber and reduces its hygroscopicity, leading to improvements in dimensional stability and resistance to biodegradation (Boonstra and Tjeerdsma, 2006; Hill, 2006).

Compared with untreated wood, thermally modified wood becomes more brittle, showing lower bending and tensile strength but higher strength in the longitudinal direction, along with an increase in compressive strength and stiffness (Boonstra *et al.*, 2007).

There are a variety of thermal modification methods that can be applied to wood, and the exact method of treatment can have a significant effect upon the properties of the thermally modified wood. Important process variables include time and temperature of treatment, treatment atmosphere, closed versus open systems, wood species, wet and dry systems, sample dimensions and the use of catalysts (Hill, 2006).

Chemical modification takes place through the reaction of different chemicals with the hydroxyl groups (OH) from wood, resulting in permanent change to the molecular structure of the wood components. The most common chemical modification of wood is its acetylation, with the commercial product known as Accoya® wood. In this case, the hydrophilic OH groups are replaced by more hydrophobic acetyl groups through acetylation with acetic anhydride. In addition to high durability and dimensional stability without the loss of strength, the acetylated wood shows significant resistance to moisture and fungi, due to the hydrophobic treatment (Hill, 2006).

A very large number of other reagents have been studied for their potential for the chemical modification of wood, but in most cases, these are unlikely to be suitable for scale-up to industrial processes.

Impregnation of wood with different chemicals, which usually diffuse into the cell wall or lumen, is considered to be a passive process because the wood properties are modified without the alteration of its chemical nature. The property change primarily comes from the bulking of wood cells by the impregnants (Hill, 2006; Ramage *et al.*, 2017). The permeability of timbers decreases, leading to a better resistance to water and fungi; the density of timber increases with an improvement in some mechanical properties. The chemicals used can be monomers that are cured into bulk within wood cells after subsequent polymerisation or different preservatives.

Another modification process is the *coating of the surface* of wood products, supplying a physical barrier against weathering and degradation and presenting the aesthetics of the product as well, which is suitable for many high-value exterior wood end uses (Ramage *et al.*, 2017).

Chemical modification and impregnation modification considerably improve the material properties of wood by reducing the water uptake and increasing dimensional stability, hardness, resistance to weathering, colour stability and decay resistance (Kielmann and Mai, 2016).

2.2.4 Wood performance

Wood performance is affected depending on the application by several factors including the moisture and temperature, defects, durability, construction details and maintenance. Wood used in exterior applications is mainly affected not only by moisture- and temperature-related effects but also by weathering and biological attack. Moisture and temperature play an important role also for indoor applications and in the building envelope. They are the essential elements for initiating physical, biological and structural degradation of wood (Nofal and Kumaran, 2011) and are related to sorption and permeability of wood. Specific type of degradation depends on the wood specie, geographic location and the environment and the biological organisms.

In order to improve the natural resistance, to slow down outdoor degradation processes and to prolong the service life of wood, several preservative treatments, modification (thermal, surface, chemical and impregnation) treatments or coating applications are used. All these show a good potential in reducing the water sorption, increasing the biological resistance and enhancing the weathering performance of wood.

The *wood quality* depends on the average characteristics of the material and the presence and distribution of the defects: (i) knots, which affect the appearance and the mechanical properties of the material; (ii) slope of grain (growing anomaly or the oblique sawing of the pieces) or (iii) cracks (due to sudden drying processes, with high gradients of moisture content in the cross section of the wood pieces), which induce discontinuity in the wood material affecting the mechanical properties.

Durability of wood consists of its natural durability and the durability created through different applied treatments. The first one—the natural durability—of a wood species is defined as its inherent resistance to wood-destroying agents (Kutnik *et al.*, 2014) through the presence of lignin and different extractive substances that are natural fungicides or insecticides. It can vary widely depending on the age of the tree, its geographical origin and the growing conditions. Therefore, the durability of wood is in the range between a few years and a few thousands of years. Moreover, the durability of wood is closely related to the environment where it is placed (when stored under cover (roofed) in stable environmental conditions, wood can maintain its properties over 1000–2000 years); therefore, it has to be expressed in terms of duration, not as a relative classification (according to European standards EN 350 (CEN, 2016)) (Kutnik *et al.*, 2014). Biological durability is the key factor determining performance for wood in different use classes (EN 335 (CEN, 2013)). The wood durability can be improved by using different treatments—thermal or chemical modification, preservatives, fire retardant and decay control chemicals—selected in accordance with the European Standards EN 351-1 (CEN, 2007a) and EN 460 (CEN, 1994).

Performance to fire of wood is considered to be poor and strongly depends on its specific surface area. For example, structural wood beams with large cross sections present high fire resistance, whilst the wood timbers with small cross section will present poor performance. The reaction to fire performance of wood can be improved by using different fire retardant or intumescent materials that react under the action of temperature, creating a 'timber's thermal insulation layer'.

Seismic performance of wood is attributed to the structural design of the building and has been considered very positive in terms of life safety. The seismic resistance of wood-frame houses depends on the following properties of the building: the shear resistance at the base, shear resistance of the exterior and interior walls and the uplift resistance of the building at the base and at floors at every storey (Rainer *et al.*, 2004). The shear resistance at the base is the primary loading effect on the structure and has to be resisted at the foundations level since the foundation (usually concrete) moves with the ground. The movement at the interface between the concrete base and the wooden structure has to be resisted by anchor bolts from the concrete through the bottom sill of the exterior shear walls. The shear and uplift in a wall element are connected by equilibrium relationships in that shear resistance requires resistance to uplift to prevent the walls from overturning.

The *construction details* may apparently improve the wood performance by taking into consideration the performance required for a certain wood element, determining the use class, the biological agents and assessing the necessary treatments (preservatives, chemical or thermal modification), addressing the security issues (if the wood element is adequate or its failure may induce dangerous consequences).

2.2.5 Applications of wood in construction

The methods used for timber construction differ from country to country. However, many similarities can be found due to the specific properties of wood and also to the movement of the skilled carpenters and techniques over the centuries.

Traditional architectures are characterised by local materials for building construction suitable for the climatic regional conditions. Along with other materials, wood has played an important role in the building constructions across the centuries (Fig. 2.6A—traditional house in Bukovina region, Romania, and Fig. 2.6B—Kōfuku-ji Temple in Nara, Japan).

Nowadays, wood is still a basic building material, used in a wide range of structural applications in foundations, light-frame construction, beams and columns, bridges, etc. At the same time, solid wood and wood-based composites receive increased attention to their utilisation in floors, ceilings and walls.

Commercial wood processing facilities normally have guidelines (grades) for acceptance of their input material, according to specific market segments. The criteria

(A) (B)

Fig. 2.6 (A) Traditional wooden house from Bukovina region in Romania (19th century) and (B) Kōfuku-ji Temple in Nara (Japan) (8th century).

usually include factors such as log diameter, length and shape, which suit the primary processing equipment, and wood quality criteria such as basic density, stiffness and visible defects. Therefore, the logs belonging to different parts of a tree are used for different processing. For example, the logs cut from the lower part of the stem can be processed into sawn timber or can be peeled to produce veneer sheets; logs from the upper parts of the stem, which are smaller in diameter and often have branches and more juvenile wood, are generally used for pulping, chipping or flaking. Further, the residues from sawmilling and peeling operations can be used as feedstock for other products or to produce heat and power.

Construction-grade timber and engineered forest products are some of the highest value products from trees. This suggests that structural use is important for economies that rely on forestry.

During the 20th century, public perception and prescriptive regulations limited the structural use of timber in Europe largely to small and low-rise buildings (Östman and Källsner, 2011). The use of timber as a construction material for domestic dwellings is well established in many parts of Europe and around the world.

Postframe and *pole buildings*—in postframe and pole buildings, round poles or rectangular posts serve both as the foundation and the principal vertical framing element. This type of construction was known as 'pole buildings', but today, with the extensive use of posts, is commonly referred to as 'postframe' construction. This type of construction was originally used with round poles for agricultural buildings, but the structural principle has been extended to commercial and residential buildings (Wacker, 2010).

Log buildings—have always been and still are the typical construction type of the rural area across Europe and their interest is increasing (from small, simple houses for vacation use to large, permanent residences). They nearly always feature wall systems built from natural or manufactured logs rather than from dimensional lumber (Fig. 2.7). Roof and floor systems may also be built with logs or conventional framing. The logs can be round (machined to a smooth, fully rounded surface) or shaped (machined to specific shapes, generally not fully round). The interfaces between logs are machined to form an interlocking joint (Wacker, 2010).

Fig. 2.7 House under construction—untreated spruce (*Picea abies*) wood logs.

Driven by institutional changes, promotion campaigns and technological development in the 1990s, novel industrial wood-frame multistorey construction practises have been emerging in some European countries. They have been attributed to contribute both to the productivity of construction (Hurmekoski *et al.*, 2015; Brege *et al.*, 2014) and to the environmental impact of construction (Hurmekoski *et al.*, 2015; Oliver *et al.*, 2014).

Until the late 1980s, wood-framed buildings with more than two storeys were prohibited by building regulations in most European countries, due to the negative perceptions arising from historic city fires. However, driven by the construction products directive adopted in the EU in 1988, the national building regulations are being revised towards functional criteria, as opposed to prescriptive criteria, thus allowing a larger number of storeys with a wooden frame throughout Europe (Hurmekoski *et al.*, 2015).

The first modern wood-frame multistorey construction projects in Europe were carried out in 1994 in Sweden. In the United Kingdom, the market share of wood frame in residential construction has increased from 8% in 1998 to 25% in 2008. In Austria and many other European countries, the wood frame is common in the single-family housing sector (Hurmekoski *et al.*, 2015).

The preferred species for log houses are those belonging to softwoods (Norway spruce (*Picea abies*)—the most common timber, silver fir (*Abies alba*) and European larch (*Larix decidua*)). The decisive factors for using them are the straightness and length of the stem and the low density. They present better insulation and are easier to dry than the hardwoods.

Foundations—treated wood is sometimes used for basement foundation walls. Basically, such foundations consist of wood-frame wall sections with studs and plywood sheathing supported on treated wood plates, all of which are preservative treated to a specified level of protection (Wacker, 2010).

Floors—in the past (18th century), the floorboards were uncoated split round timber or boards. This technology was gradually replaced by industrial sawing, which produced boards in standardised and more uniform dimensions. The change in the manufacturing process influenced the floor assembly and the choice of wood species. The most common species were spruce (*P. abies*) and Scots pine (*P. sylvestris*). The dimensions of the boards were usually the same width as the log (35–40 cm), and the thickness was 5 cm, but later, when the sawmills became a common method for producing sawn timber, their dimensions were decreased to reduce the loss of the material. Later (from the middle of the 20th century), the boards were sawed mostly from sapwood with the same dimensions, heartwood being used for beams (Vahtikari *et al.*, 2012). Today, the boards are usually sanded, and the surface is finished with coating before installation. Even today, boards are usually installed pith side upward, which might follow from the old splitting tradition. Reducing the dimensions of the boards and use of engineered materials made today a larger availability of the wood species to be used for the floors (Fig. 2.8).

Roofs—the simplest type of roof structure consists of two single rafters that rest on each other with a hinged joint at the top. In mediaeval buildings, the crosswise load-carrying system of the common rafter roof with tie beams on every truss has

(A) (B)

Fig. 2.8 (A) Wooden floor and pillars in Shizutani School, Bizen, Japan (17th century) and (B) wooden floor in a new building.
(B) Courtesy and with permission of Prof. Miha Humar.

(A) (B)

Fig. 2.9 Wooden roof of (A) the Great Hall in Edinburgh Castle (1511) and (B) Bubenei Bridge in Schüpbach, Switzerland (1988).
Courtesy and with permission of Dr Daniel Ridley-Ellis.

been used throughout Europe (similarities have been found in northwestern countries (Sweden, Norway, Denmark, England, France and Germany) but also eastern parts (such as Romania)) for the Romanesque roof structures (Fig. 2.9).

Arch structures are particularly suited to applications in which large, unobstructed areas are needed, such as churches, recreational buildings and aircraft hangars.

Wood decks—a popular method of expanding the living area of a home is to build a wood deck adjacent to one of the exterior walls. Decks are made of preservative-treated lumber. To ensure long life, acceptable appearance and structural safety, several important guidelines should be followed. Proper material selection is the first step. Then, proper design and construction techniques and, finally, proper maintenance practises are necessary (Wacker, 2010).

Timber bridges—prior to the 20th century, timber was the major material used for both highway and railroad bridges. The development of steel and reinforced concrete provided other options, and these have become major bridge-building materials. Bridges consist of

Fig. 2.10 Wooden bridge.
Courtesy and with permission of Dr. Daniel Ridley-Ellis.

Fig. 2.11 Vertical façade made of thermally modified spruce wood.
Courtesy and with permission of Prof. Miha Humar.

a substructure and a superstructure. The substructure consists of abutments, piers or piling, and it supports the superstructure that consists of stringers and/or a deck (Fig. 2.10). Timber may be combined with other materials to form the superstructure (Wacker, 2010).

Wood facade claddings made of natural wood or wood treated in different methods can be carried out in various ways, depending on desired effects, horizontal, vertical and diagonal (Fig. 2.11). The main function of the cladding is the protecting of wind barrier and insulation layer in a wall from rain and solar radiation. Sheet materials, board claddings, shingles and a variety of other materials can be used. The alterations in appearance due to colour changes, modifications of surface structure and biological surface growth modify the aesthetics of a wooden cladding significantly (Rüther and Time, 2015). Both coniferous and deciduous species are used for façade claddings, with spruce (*Picea* sp.), larch (*Larix* sp.) and pine (*Pinus* sp.) as common examples of coniferous species and oak (*Quercus* sp.) and hornbeam (*Carpinus* sp.) as common examples for deciduous species (Ivanović-Šekularac *et al.*, 2016).

Natural and modified or treated wood is also commonly used for window and door manufacture.

2.3 Cross laminated timber

P. Wilson
Timber Design Initiatives Ltd, Edinburgh, United Kingdom

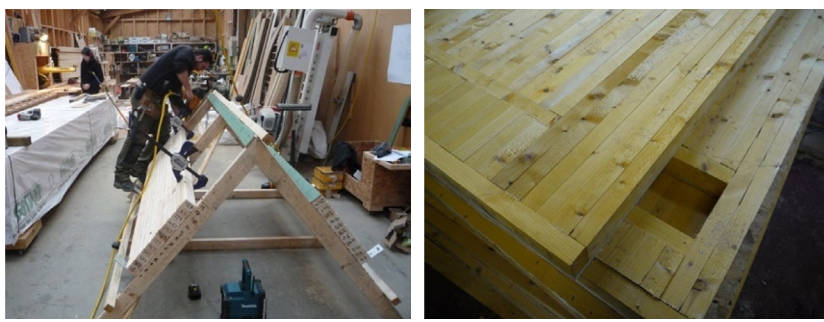
2.3.1 Background

Cross laminated timber (CLT) was first conceived in the 1980s by Julius Natterer, a German engineer and professor for timber at the Ecole polytechnique fédérale de Lausanne, in response to what in Switzerland at that time was deemed to be over-production in the nation's forests and a consequent oversupply of low-grade timber. Natterer's innovation was to produce a high-value product from lower value stock, by laminating wood planks together with the use of nails, screws or dowels (Fig. 2.12A and B) to form solid, one-way spanning panels: effective glue lamination without the use of glues.

This concept moved quickly to incorporate the idea of two-way spanning timber plates (Fig. 2.13) in which each wood layer was glued at right angles to the next, the final panel comprising an odd number of layers to ensure that the grain of the two outer lamellae always ran in parallel with their longest dimension.

In its earliest commercial form, CLT was manufactured using a vacuum press, but it did not take long before hydraulic presses were employed to produce panels in ever larger dimensions. Importantly in the early days, the link between forest, sawmill and manufacturing facility was effectively umbilical, with little or no transportation and fuel requirements between each stage of the process, thereby excising most of the embodied energy costs normally associated with industrial production.

In its earliest forms, strips of wood (usually of species commonly grown in Central Europe such as spruce and fir), kiln-dried to a moisture content of 12%–14% or less, were finger jointed to create long lengths of material that could be placed side-by-side to create a large single panel layer (lamella). This was then coated with a layer of polyurethane adhesive (this solvent-free and formaldehyde-free glue sits within



(A) (B)

Fig. 2.12 (A) Small-scale production of nailed stacked plank panel system and (B) completed nailed stacked plank panel for use in housing service core module.

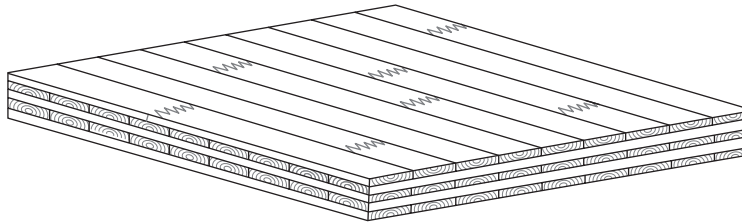


Fig. 2.13 Diagrammatic arrangement of cross-laminated timber lamellae.

the '0' emission class and can achieve a very high quality level of adhesion with no risk of toxic emissions at any stage in the product's life cycle), and a second layer of wood strips laid on top at 90 degree to the first to form the next lamella. This process continued until three, five, seven or nine layers were in place, the whole then to be fixed together with the application of hydraulic power to specific pressures calculated to ensure each panel was of defined—and consistent—structural strength, stiffness and dimensional stability. Crosswise glueing at high pressure in this way reduces the wood's expansion and shrinkage to an insignificant level.

Later, some multinationally based manufacturers such as Stora Enso developed production processes whereby each wood strip was not only finger-jointed but also edge-glued to the next so that each individual layer was in itself a homogeneous glued plate capable of being lifted by suction and mechanically manoeuvred into position within the factory space—a method that dramatically reduced the physical handling of materials and increased the size and speed at which CLT panels could be fabricated.

The evolution of CLT has thus—at least in Central Europe, where the vast majority of manufacturing plants exist—been one in which the locally prevailing forest species and existing sawing patterns in the mills have, until relatively recently, largely determined the dimensions of the finished product. In many cases, the manufacturers have been family-owned sawmills (such as Schilliger Holz in Switzerland), each producing their own variation of CLT. Whilst this created a highly competitive market, it also had downsides, not the least being that individual producers worked to different overall lamella dimensions, resulting in inconsistency between manufacturers in panel lengths, breadths and depths. This issue has often proved problematic for specifiers and cost consultants—like could not be compared with like—and resulted in an unanticipated market constraint that the larger manufacturers have since sought to work together to address.

The same has not been true in North America: The Canadian timber industry recognised the product's future potential, and under the Transformative Technologies Programme of Natural Resources Canada, FP Innovations carried out an international fact-finding mission and a multidisciplinary research programme in 2005 that resulted in the publication of the peer-reviewed CLT Handbook (Gagnon and Pirvu, 2011), a substantial document with chapters covering manufacture, structural design, seismic performance, connections, duration of load and creep factors, vibration performance, fire performance, acoustic performance, environmental performance and building enclosure design using CLT. Importantly, it stipulated that any manufacturer in Canada

must produce panels to specific dimensions in order to conform to the construction regulations prevailing in the United States, the largest export market for Canadian wood products.

Austria, however, remains by far the biggest producer of CLT and indeed the largest exporter of the product, a situation likely to be the case for some time, since two of its most important markets—Italy and the United Kingdom—manufacture little or none of it at present. Austrian exports of CLT have been employed in new building projects as far apart as Melbourne and Vancouver, in both instances panels produced by *KLH* Massivholz (KLH, Kreuz Lagen Holz, which translates as 'cross-laminated timber') being the product of choice. Indeed, KLH was the first company to put CLT into large-scale production, its first panels appearing in Austria in 1998–99. Given its substantial available resource of good quality timber and the Austrian industry's preparedness to invest heavily in CLT production, the country's manufacturers are, by some margin, also the largest, again a situation unlikely to change for some time, with KLH, Mayr-Melnhof Kaufmann and Stora Enso as the leading players, whilst companies such as Binder Holz have been important manufacturers since the product first appeared.

One other aspect of Austria's leading position should be mentioned: the initiation in the mid-1990s of an industry-academia joint research programme that resulted in the development of CLT as we now know it. Crucially, this research has been the recipient of considerable investment by the Austrian timber processing and manufacturing sectors, a factor inseparable from the country's continuing lead in the product's development. This is not to say that manufacturers in other Central European countries are small—southern Germany, Switzerland and Slovenia each produce considerable volumes of CLT—and around the world, new plants are emerging at speed and in numbers as the benefits of local production from local raw material are increasingly recognised.

2.3.2 Why has the use of CLT expanded so rapidly?

CLT has many advantages over more traditional construction materials. First and foremost, it is an innovative engineered timber product created from the world's leading renewable resource—our forests. The technology itself—glue lamination—is not of course new, but the well-known glulam beam is a one-way spanning engineered timber product in which the grain in all the lamellae are glued in the same direction, whereas the introduction of cross lamination created the possibility of two-way spans without the need for additional reinforcement as is required in concrete panels. The manufacturing process too has not been shown to create significant environmental issues, unlike the production of concrete, now widely recognised as the construction industry's primary (and very substantial) contributor to global greenhouse gas emissions.

These benefits, whilst laudable, would not in themselves be regarded as sufficiently transformational to have impacted so dramatically upon the construction of buildings of all types in such a relatively short space of time, and it is in conjunction with the development of computer numeric cutting (*CNC*) machine technology that the advantages begin to manifest themselves more clearly. Most equipment of this sort employs 4-axis geometry to cut in almost any direction, with all waste produced in the process

contained to the factory and recycled for other uses such as the manufacture of pellets for use in kiln-drying.

The ability to go from the design drawing on the architect or engineer's computer directly to the factory where panels can not only be cut precisely to size but also to have material removed to create window and door openings and recesses routed into the depth of the plate for electrical cabling, drainage and other mechanical services is hugely advantageous in construction (the panels have excellent dimensional stability, both in overall panel size and for structural openings). Prefabrication of this sort allows panels to be assembled on-site to within 2 mm tolerances, a degree of consistent accuracy largely unknown with traditional on-site construction methods. High levels of prefabrication do require more time to be spent at the early design stages to ensure all of the required cut-outs are preplanned and included in the digital drawings transmitted to the CNC machines. The extension of time required for this compared with other design methods is more than offset by the subsequent speed of on-site assembly in which time and consequent cost savings can be considerable.

Speed, indeed, is an important prerequisite in construction nowadays: building in cities especially can require many deliveries to site with attendant traffic delays causing sequencing and on-site storage problems. A building whose structure is largely composed of CLT panels can require many fewer vehicle deliveries than heavier materials such as panelled or in situ concrete; it is easier and quicker to offload—often without the need for on-site cranes (the task being achieved either with Hiab equipment on the trucks or with portable cranes)—and, importantly in urban situations, with relatively little noise. This last characteristic has been shown to be increasingly valuable in mitigating complaints from adjacent residents during the construction period.

Speed in erection too is of immense value—using panels in an approach similar to platform-frame construction means each floor plate supports a wall panel that then supports the next floor plate and so on. Lifting panels directly from trucks into position (Fig. 2.14) rather than to on-site storage areas means not only that tight urban

Fig. 2.14 Cross-laminated timber panels being craned directly from truck into position on building.

sites can be developed quickly but also that as the building raises other trades can be brought on sooner to work on levels of the building already in place. Considerable evidence now exists of complete, multistorey buildings being erected in days rather than weeks, and time-lapse photography of on-site progress is now a major selling point to clients and contractors unfamiliar with this construction method.

Other urban benefits of CLT construction range from the fairly obvious to the less evident—at least until made aware of them. Invariably, this lighter weight technology requires less on-site plant and equipment and fewer construction staff to be involved in the assembly process.

Advance planning of the panel arrangement by experienced timber engineers is crucial to the way in which the vertical loads are distributed through the structure, whilst—at its simplest—the method of fixing panels is very simple in that it involves the use of metal angle brackets (Fig. 2.15A) and very long steel screws (Fig. 2.15B) to connect walls to floors, with metal anchors fixed through the floor plates and connected through the thickness of the wall panels to provide shear strength to the overall structure. In all of this, very little, if any, on-site modification is required to the prefabricated panels (presuming well-considered advance planning and design has taken place), the result being the production of minimal on-site waste.

But it is in the lighter weight of the overall structure that one of the most important urban benefits is to be found: In London, for example, many of the available sites lie above 19th century brick sewers or underground transportation routes, making deep pile foundations impracticable. CLT structures have the great advantage of being capable of erection on lighter foundations—a cost saving in itself—and thus on otherwise difficult-to-develop sites (Mayo, 2015; Fig. 2.16).

In other more challenging urban locations, CLT construction may also—up to predefined heights—obviate seismic concerns as extensive testing has shown these structures to have considerable resilience in earthquake situations.

(A) (B)

Fig. 2.15 (A) Connecting cross-laminated timber floor and wall panels using metal angle brackets and shear anchors and (B) long steel screw fixings driven into cross-laminated timber wall and floor plates at 45 degree angle.

Fig. 2.16 Canal infrastructure required lighter foundations to cross-laminated timber structure of apartment/studio building in Whitmore Road, London, by Waugh Thistleton Architects.

Much of the above applies to the erection of buildings employing CLT in their structural design, but there are significant benefits to be had from the use of this solid timber technology in three important areas: the need for fewer additional layers of building materials such as internal wall linings and ceilings when—depending on building type and local building regulations—it is possible to leave the internal panel surfaces exposed. Aside from the reduced costs and timescale savings that come with this, there are valuable thermal advantages to be realised due to the material's inherent insulating qualities (Fig. 2.17). The exposed surfaces too can offer improved internal air quality due to the hygroscopic nature of the timber. In the final analysis, however, the biggest environmental gain from the use of CLT is in the ability of solid wood to sequester substantial amounts of atmospheric carbon dioxide throughout the lifetime of the building and beyond, the latter depending on the nature of the subsequent use of the panels following the deconstruction of the building.

2.3.3 CLT—Properties and performance

CLT has many construction and environmental advantages over other building materials all of which are derived from the product's properties and performance in use. Predominantly manufactured from softwoods such as spruce or pine, the multilayer cross-laminated panels have a density (depending on species used) of between 430 and 470 kg/m^3, a significant handling and transportation advantage over concrete (density 2400 kg/m^3) or steel (7850 kg/m^3). This also has benefits for foundation design,

Fig. 2.17 (A) Fair-faced surface of cross-laminated timber interior of artists' accommodation in Trondheim, Norway, by Brendeland & Kristofferson architects and (B) passive control of relative humidity and temperature in architectural drawing archive building by Hugh Strange Architects is provided by the ultra-thick cross-laminated timber used to form its walls and roof.

with CLT generally requiring much lighter foundations than required by concrete, masonry or steel superstructures.

The two-way spanning characteristic of CLT has been critical to the speed at which it has infiltrated the construction market, opening up the possibility of building timber structures taller than seven storeys. The cross-lamination glueing process gives the product dimensional stability, and ongoing measurements at the Stadthaus in Murray Grove since 2008 indicate minimal vertical shrinkage in the structure. This is an extremely durable product.

Two other factors have assisted in the take-up of CLT: first, the product's excellent performance in fire, since the external surfaces, once charred, cease to continue burning, leaving the core timber structurally intact. This is a phenomenon that can be calculated: The species used in the manufacture of CLT have been shown to burn at a rate of 0.7 mm/min, and so to achieve R30 (30 min fire resistance), a char zone of 21 mm is added to the structural dimensions required. Similarly, R60 requires 42 mm, R90 63 mm and R120 some 84 mm, all as stipulated in EC5 Part 1.2, Table 3.1.

The second reason CLT has taken hold in the world of tall building design is the product's ability to store large amounts of atmospheric CO_2. One cubic metre of wood stores 0.8 tonnes of atmospheric CO_2, meaning that a typical timber frame house containing ~14–20 m^3 of wood stores 11–16 tonnes of atmospheric CO_2. By comparison, an equivalent house constructed from CLT stores around four times as much, that is, 56–80 m^3 of CLT will store 45–64 tonnes of atmospheric CO_2. When multiplied over a large urban development such as the 8–11-storey housing project at Dalston Lane in London by Waugh Thistleton Architects, the 10,000 tonnes of concrete structure that would otherwise have been required is instead replaced with 4050 m^3/1930 tonnes of CLT to deliver some 10,000 m^2 of floor space and provide homes for some 800 people.

CLT has a range of other properties beneficial to both health and well-being. Its precision manufacture ensures extremely good airtightness, and the hygrothermal inertia of the panels helps deliver good thermal performance. The hydrothermal ability

of CLT to absorb and desorb moisture also contributes to improved internal air quality, whilst studies in Norway indicate psychophysiological benefits: children taught in solid wood rooms have been shown to have heartbeats down by around 6/min.

Increasing awareness of the potential of CLT in construction has led to the emergence of more creative building designs, but these are fundamentally premised upon a series of consistent performance characteristics of the product, both in manufacture and assembly. Being prefabricated, the panels are delivered directly to the building site and uploaded directly on to the construction, thus reducing site storage requirements which, in tight urban situations, can require complex manoeuvres. Speed of construction is thus improving a factor enhanced by simple connection details that do not require large numbers of highly skilled on-site personnel. This plus reduced noise from on-site activity and minimal on-site waste have added to the product's attractions. One other characteristic should also be noted—CLT has performed extremely well in a wide variety of seismic tests in which the fundamental elasticity of the structures under examination has ensured their resistance to collapse.

2.3.4 The application of CLT in different building types

In its earliest days, CLT was invariably regarded as a wood-based substitute for prefabricated panels manufactured from other materials such as reinforced concrete and steel, and the available evidence indicates its employment—other than in small-scale domestic architecture—was primarily in repetitive or cellular applications: the equivalent of tunnel form construction using precast concrete or in the manufacture of volumetric units that could be stacked to form larger assemblies. Building types suited to this approach were hotels, hospitals, homes for the elderly, administration facilities, etc., and in this context, Austrian architect Hubert Riess was an early pioneer in the conception and design of prefabricated, modular residential and office complexes based on the new commercial availability of very large CLT panels. In the first decade of the 21st century, Riess produced a string of influential designs that explored the opportunities offered by a new product made from a renewable material (Kapfinger and Wieder, 2007). Much of this endeavour was also focused on the densification of the urban environment, a perennial challenge that remains with us today and one that CLT and other engineered mass timber products are increasingly being used to address.

2.3.4.1 The game changers

In recent years, CLT found new opportunities in existing large-scale building types such as schools, supermarkets and tall commercial and residential structures. 'Building Schools for the Future' (Burr, 2009) was the name given to the UK government's highly ambitious investment programme in secondary school buildings in England in the first decade of the 21st century. Costed at £55 billion and with a target to deliver 250 schools a year, CLT construction was quickly seen as a potential solution to the cost and timescale challenges inherent in such a politically driven agenda. Fourteen local education authorities took part in the first wave of the Building Schools for the Future programme for the fiscal year 2005-06, and by Dec. 2009, 96 local authorities

had joined the programme. In 2007, the programme was complemented by the announcement of a Primary Capital Programme, with £1.9 billion to spend on 675 building projects for primary schools in England over three years. Whilst the delivery of these programmes was carried out in waves, the percentage of buildings constructed from CLT panels was remarkably high, given the product's relative anonymity in UK construction prior to this. There is no doubt that speed and simplicity of assembly, relatively low requirements for skilled on-site labour and cost at a time when steel prices were high (demand from China being great) and—to a lesser extent—CLT sustainability credentials all contributed to its emergence as a primary choice for large-scale projects of this sort.

Global demand for steel and its consequent high price and the sustainability credentials already mentioned unquestionably brought the product to the attention of the retail sector and in particular to supermarkets. Conventionally, the domain of steel frames and metal cladding systems and the attractions (for a client base sensitive to customer perceptions) of an environmentally responsible structural system were significant and early projects combined a glulam post-and-beam approach with walls and roofs formed from CLT. Aside from certainty of delivery dates, speed and precision of erection and the aforementioned environmental benefits, clients discovered not only that throughput of customers (and thus cash flow) could be achieved more quickly but also that people found the timber internal environments to be more comfortable and, as a consequence, were spending more time and money in the stores, an initially unforeseen, but thereafter compelling, benefit.

The third building type that can legitimately be described as a 'game changer' as regards the use of CLT was in its potential to build higher than previously possible with timber frame systems. Until 2008, when the 9-storey Stadthaus (Bernheimer, 2014; Green, 2012; Thomson, 2009; Fig. 2.18A) was completed in the east London Borough of Hackney, the development of timber construction—particularly in the United Kingdom—had been based upon platform frame technology, a method of building that is effective up to seven storeys in height, although due to local building regulations in many jurisdictions (including international) is invariably restricted to five storeys or less.

The Stadthaus' eight storeys of CLT arranged in a honeycomb structure (Bernheimer, 2014; Green, 2012; Thomson, 2009; Fig. 2.18B) above a single-storey masonry plinth designed by Waugh Thistleton Architects and Techniker engineers changed this forever. This residential building in a dense area of London ticked multiple boxes for the local authority, not the least being its carbon credentials. Speed of erection, limited deliveries, low noise during construction and minimal waste generated all added to the attractions of this approach to building in the city, and Hackney has since become something of a world epicentre for dense urban residential structures formed from CLT. Most of these are within the 8–10-storey range, but the fact that they are there at all—in a city whose building acts are predicated on the Great Fire of London in 1666—is testament to how far the product has come in a relatively short period of time, a fact confirmed by the sheer number of tall residential CLT structures currently being built or proposed in all parts of the globe.

Fig. 2.18 (A) The Stadthaus 9-storey cross-laminated timber apartment building in Murray Grove, London, by Waugh Thistleton Architects and (B) cutaway illustration of honeycomb arrangement of the Stadthaus's cross-laminated timber structural system.

Structural engineers immediately recognised the implications of what had been achieved with the Stadthaus and began to explore the vertical possibilities of engineered timber construction. Techniker themselves quickly published indicative designs for timber buildings up to 30 storeys in height and, whilst not developed in detail at the time, caught the attention of engineers around the world. By mid-2009, engineered timber technology and timber engineering itself were beginning to catch up with the imagined opportunities, with the Limnologen (Mayo, 2015; Perkins, 2014) complex of four towers each 8 storeys high constructed at Växjö in Sweden employing a hybrid glulam post-and-beam structure with CLT floors, walls and cores above first floor level. Around the same time, another CLT structure—holz8—was being completed at Bad Aibling (Kaufmann and Nerdinger, 2011; Perkins, 2014) in Germany as a pilot project intended to test the merits of mass timber construction and energy efficiency. This 8-storey building had a concrete core, but the 10-storey Forte building (Mayo, 2015; Perkins, 2014), designed and constructed by Lend Lease in Melbourne in 2012, eschewed this solution and used imported CLT (manufactured by KLH) for all elements including stair shafts and elevator core. The largest urban project to be conceived and realised at the time, however, was the Cenni di Cambiamento (Perkins, 2014) project in Milan, a social housing complex comprising four 9-storey towers with 2-storey connector buildings. Although not the highest timber structure when it was completed in late 2013, this project undoubtedly pushed the technology further by using two complex connection systems at the junctions of the CLT panels to ensure seismic stability.

2.3.4.2 Tall timber buildings/the vertical timber city

Moving beyond the 10-storey level—a height limitation often more to do with local building regulations than the capacity of structural engineers to design taller buildings with new engineered timber products—has taken a little longer, since the process of design and the gaining of planning approvals can take more time than perhaps anticipated, but projects are now emerging that make a quantum leap in vertical timber structures. The design of the Treet building (Fig. 2.19) in Bergen began in 2005, with construction completed in 2015 and is, at 14 storeys, currently the world's tallest residential timber building. This will be overtaken in the summer of 2017, however, when the 18-storey Brock Commons student residence at the University of British Columbia in Vancouver is officially opened.

In many ways, it is not surprising that the lead position in this particular race is shifting to Canada, as this can be seen as a direct consequence of the determination within the forest and timber processing sector there to take advantage of a technological development that has the capacity to incrementally increase the value of the vast resource of raw material the country has available. Indeed, Vancouver-based architect Michael Green was commissioned by the Canadian Wood Council (*CWC*) to produce 'Tall Wood' (Green, 2012), a downloadable research report that explored the possibility of commercial buildings up to 20 storeys in height being formed from hybrids of glulam and CLT. This work, whilst freely available under a Creative Commons licence (downloadable PDF), not only indicated the potential for mass timber structures in building types other than residential but also has seen the architect himself follow up with a series of proposals for 30- and 35-storey towers in Vancouver and Paris, respectively, and designs for entire urban districts composed of tall timber structures—the idea of vertical timber cities now being eminently realisable.

The endeavour in North American is not confined to Canada; however, the 'Tall Wood Building Prize to Innovate Building Construction' was launched as an architectural design competition in October 2014 as part of the Obama administration's

Fig. 2.19 Fourteen-storey Treet building in Bergen formed from glulam trusses and cross-laminated timber modules.

Fig. 2.20 (A) Twenty-storey apartment blocks proposed for Stockholm Waterfront by Tham & Videgård Arkitekter, (B) 34-storey glulam and cross-laminated timber Västerbroplan apartment building proposed for Stockholm by C.F. Møller Architects and (C) speculative 80-storey Barbican Oak project by PLP architects, Smith & Wallwork Engineers and Department of Architecture at Cambridge University.

commitment to mitigating climate change in the United States and focused heavily on CLT and other emerging timber technologies. With a prize of $2 million available, the process produced not one but two winners, with 12-storey timber towers to be built in both Portland and New York. Far from being a passing enthusiasm on that side of the Atlantic, there is currently a bill in front of the US Senate 'to accelerate the use of wood in buildings, especially tall wood buildings, and for other purposes'. Following recent political developments, the future of this initiative is unknown, but if enacted, it will enter the legislative domain as the 'Timber Innovation Act of 2016'.

Back in Europe, designs for a plethora of tall, engineered timber buildings are in process: four 20-storey apartment blocks for Stockholm's waterfront proposed by Tham & Videgård Arkitekter (Fig. 2.20A), the 24-storey HoHo tower in Vienna designed by *RLP* Rüdiger Lainer+Partner and the 34-storey Västerbroplan (Fig. 2.20B) residential tower in Stockholm by C.F. Møller Architects. In each instance, the boundaries of timber engineering are being pushed ever further, but the example that perhaps takes this endeavour to a completely new level is the Barbican Oak project in the City of London (Fig. 2.20C), a research project exploring the possibility of building up to 80 storeys in timber and initiated by *PLP* Architects in London, Smith and Wallwork Engineers in Cambridge and the Architecture Department at Cambridge University. Undoubtedly provocative and—to some—highly questionable, it nevertheless raises many technical and wood science questions, the response to which may well expand the boundaries of engineered timber technology and manufacture far beyond current understanding and industry capacity.

2.3.4.3 Where to now for CLT and other engineered timber products?

The modern world of bio-based construction materials is the product of some extraordinary research and development that has pushed our scientific and technical understanding into completely new areas. Inevitably perhaps, wood has been to the forefront in this,

it being one of the most readily available of raw materials. The transformation that has been effected in the field of engineered timber products and systems has opened a whole new domain of construction possibilities that can be viewed as still being in the early stages of evolution. To date, most applications of these new products have been applied in traditional, orthogonal ways, whilst the technologies themselves, with the increasing availability of 8-axis robotised CNC machines, suggest not only that completely different building forms are possible but also that the standardised panel is not the only route to the future: bespoke panels manufactured in response to the design imagination are already on the horizon and will move the technology beyond the present situation in which designers learn to work within the limitations of existing factory product.

2.4 Panels

S. Curling, J. Kers†*
*Bangor University, Bangor, United Kingdom
†Tallinn University of Technology, Tallinn, Estonia

Wood-based panels are widely used construction materials, consisting traditionally of some form of wood bound together by a glue or resin using heat and pressure. As engineered products, they have reduced variability in some properties compared with natural solid wood, making them a more predictable product. There is considerable information available about the many types and uses of wood-based panels, and this section will briefly summarise the manufacture, properties and applications of the major panel types.

Wood panels can be broadly classified into differing types based on the form of the wood that is used in their construction (Fig. 2.21):

- *Plywood*—formed of multiple plies or rotary peeled veneers of wood which are glued and cross-laminated together.
- *Particle boards* (chipboard)—formed from wood that has been reduced to particles, bound together using resins by heating under pressure. The particles are generally small, for example, $1 \times 1 \times 0.25$ cm with larger fractions on the inside and smaller fractions on the surfaces of the boards. The particles are not aligned in any direction.
- *Oriented strand board* (*OSB*)—OSB is also formed from wood particles, but in this case, the particles are in the form of 'strands' or 'wafers' and have a larger aspect ratio than those in particle board (at ~$2 \times 7.55 \times 0.25$ cm). The strands are orientated in the major direction of the board itself.
- *Fibreboard*—these boards are constructed from wood reduced to fibres that are then bound together by water or resin using heat and pressure. Again, these types of materials can be subdivided based on the manufacturing process with a 'wet' process used to make softboard (*SB*) and hardboard (*HB*) and a 'dry' process used to make medium-density fibreboard (*MDF*)

The density of wood panels is dependent on the wood used and the processing variables; the boards can be manufactured to represent the whole range of wood densities found in timber (Fig. 2.22).

Fig. 2.21 Wood panel products—from top, plywood, OSB, chipboard and MDF.

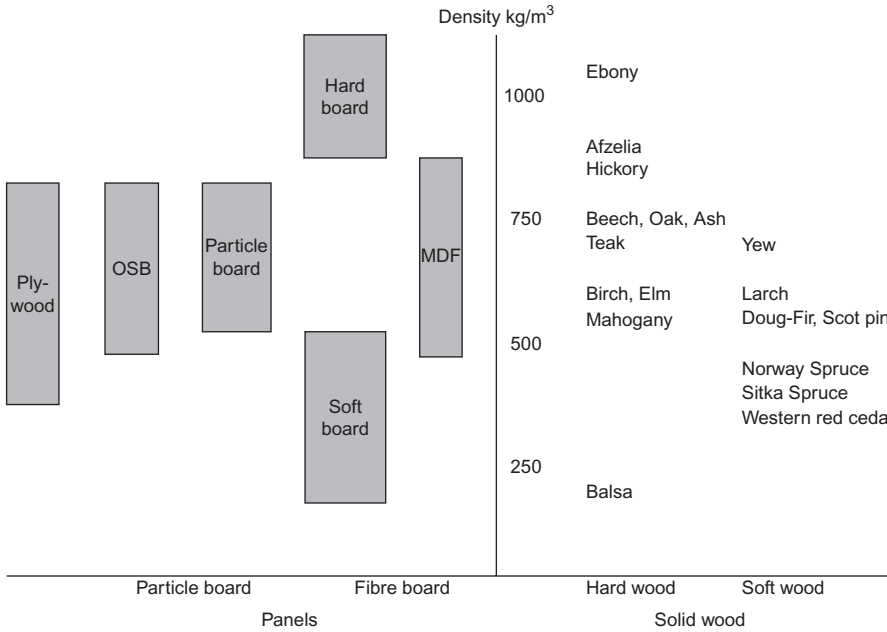


Fig. 2.22 Comparison of the density of wood panels compared with selected wood species (Curling, 1998).

In most cases, the wood particles are bound together using a resin system that traditionally has been a formaldehyde-based resin. The three major types are urea formaldehyde (*UF*), melamine urea formaldehyde (*MUF*) and phenol formaldehyde (*PF*) that impart differing moisture resistance and strength properties on wood panels, with PF resin generally having the higher performance. Non-formaldehyde resins are also used, for example, methylene diphenyl diisocyanate, though this has cost implications. Having a formaldehyde-based resin has led to issues with indoor air quality, as the panels are known to 'off gas' and release formaldehyde for some time after manufacture (Savory, 1969; Curling and Murphy, 1999).

2.4.1 Plywood

Plywood is constructed from plies or veneers of wood glued together, a technique that may have been used in some form for thousands of years. Actual structural plywood has a more limited history with first mentions made in the 18th century. Subsequently, plywood has been used in construction, interior furnishings and even aircraft (Stark *et al.*, 2010).

Manufacture. Plywood is a board material constructed from an odd number of (usually three, five, seven, etc.) sheets of wood, termed plies, that are bonded together using a glue (traditionally a urea or PF ~5%–10% by weight dependent on type). In recently developed plywood (*UPM* Grada), the thermoplastic film glue can be hot-melted again (90°C or 130°C), which makes this material thermoformable. When arranging the sheets, the layers are aligned so that the grain of the wood of each ply is perpendicular to that of the plies it is bonded to. Therefore, all odd-numbered layers have a grain orientation parallel to the long dimension of the panel, whilst all even numbered plies have a grain orientation perpendicular to the long dimension. The wood used can be either soft or hard wood origin, based on the timber availability and desired end use. Spruce, pine, fir, birch, beech, poplar and eucalypt are all commonly used. (For a more detailed description, see Thoemen *et al.*, 2010; Hughes, 2015.)

A simple scheme of manufacturing plywood includes a number of processes; the logs are debarked, and veneer is peeled or sliced, checked for defects, cut to obtain the required sorted quality and dimensions and dried; glue is applied; and then, the boards are cold and hot-pressed to cure the glue. Finally, the boards are finished by sanding or by application of coatings or laminates.

Properties. The characteristics of plywood are heavily influenced by the wood species, the number of plies and the type of resin used for glueing (Stark *et al.*, 2010; Wood Panels Industry Federation, 2014a). In general terms, plywood has good mechanical properties, which are based on the strength of the wood species but enhanced by the cross-laminated design (Cai and Ross, 2010). This gives good bending and shear strength both along and across the panel. The good mechanical properties give good resistance to splitting, which enable strong fastenings to be made, even with fasteners near to the edge of the panels. The higher strength-to-weight ratio of plywood compared with the comparable solid wood makes it ideal for flooring use. Plywood also shows good and uniform dimensional stability across the panel with low edge swelling seen with increased moisture. The actual moisture resistance of plywood

Table 2.2 European classification of plywood, according to EN 636 (2015)

Plywood classification		EN 314 bonding class	Eurocode 5 service class	EN 335 use class
EN 636-1	Dry conditions	1	1	1
EN 636-2	Humid conditions	2	2	1 and 2
EN 636-3	Exterior conditions	3	3	1, 2 and 3

is more heavily dependent on the adhesive used. For waterproof grades, PF glues, impregnated paper laminates (for the surface finish) and painted edges are used. If exposed to moisture extremes, the cross-laminated nature reduces shrinkage and warping of the panel in contrast to comparable solid woods. It can also be treated relatively easily to increase its resistance to chemicals, fire or biological attack.

Plywood can be categorised based on its use, with common classifications including structural, decorative (exterior and interior) and marine grades. In Europe, plywood is categorised (EN 636 (CEN, 2015)) based on the usage of the product (Eurocode 5 (CEN, 1995)), hazard class of the environment (EN 335 (CEN, 2013)) and the adhesive bonding of the plywood (EN 314 (CEN, 1993)) as shown in Table 2.2.

Applications. As noted, plywood has inherently good strength properties that can be engineered for certain uses. In structural terms, plywood can be used for partitions, floors, ceilings and sheathing. It is also used for decorative purposes both in exterior positions, such as cladding and doors, and internally as cabinets, shelves and furniture. The highest specification of plywood is used for marine environments, such as boats and docks—this uses veneers made from durable wood species, for example, okoume and PF resins. Requirements for untreated tropical hardwood veneers and glues for marine grade plywood are specified in the European standards EN1088-1 and EN 1088-2 (CEN, 2003a,b).

2.4.2 Particleboard

Particle board, as a product, dates from the early 20th century and developed in use during the World War II to utilise inferior wood and wood waste when good quality wood was in low supply (Stark *et al.*, 2010). Particle board is produced by reducing timber to particles, generally less than 2 mm in any dimension. These are then formed into a panel and bound together using an adhesive resin, traditionally UF or PF. Other resins can and have been used, for example, isocyanates, and there is ongoing research into utilisation of non-formaldehyde-based resins due to concerns over indoor air quality. Many particle boards are manufactured using a layering system, where the core of the board consists of large particles and the outer layers are finer particles, allowing improved surface finish. Technology for particle board manufacture has developed so that sawdust, mill residues and recycled wood can be used. Other non-wood lignocellulose materials have also been used for particle boards, for example, bagasse (Carvajal *et al.*, 1996; Xu *et al.*, 2009; Monteiro de Barros Filho *et al.*, 2011).

Manufacture. In brief (for a detailed description, see Thoemen *et al.*, 2010; Nishimura, 2015), the manufacture of particle board involves the debarking of the wood which is then cut into small chips or flakes using a 'chipper' and then subsequently further reduced in size. This secondary reduction is accomplished in a number of different ways, for example, hammermill (grinding and crushing) or knife systems (cutting and slicing). Disc refiners may also be used to produce very fine particles, for surface finishes, via attrition. The particles are then dried before being sprayed with resin (differing resin amounts may be used for core, e.g. 6%–12%, and surface layers, e.g. 4%–8%), and a mat of chips (coarse in centre and fine on surface) is formed. The mat is then pressed, in either a continuous or batch process, at high temperature (e.g. 200°C). Finally, the boards are cut and trimmed to size and finished by sanding or by addition of any coating or lacquers or high-pressure (*HPL*) or low-pressure (*LPL*) melamine-impregnated paper laminate.

Properties. Particleboard by its reconstituted nature has very uniform properties across the board in all dimensions. The resin system used has a major impact on the properties of the board with higher resin loads of moisture stable resins being used for the higher-grade panels. The strength of the boards is generally lower than plywood, having a MOR value of 16–22 MPa compared with the 35–45 MPa of plywood (Stark *et al.*, 2010; Cai and Ross, 2010).

Chipboard also has a tendency for low water resistance though this can be modified by using moisture-resistant resins (Wood Panels Industry Federation, 2014b) and additives (giving the panel a greenish colour in cross section). Particle board is classified in Europe, based on use, by the EN 312 (CEN, 2010) standard (summarised in Table 2.3).

Particle board is usually coated or laminated to improve its aesthetic value and is easily treated with fire retardants (for which the cross section is usually reddish in colour) or with preservative chemicals.

Applications. Particle board is one of the more ubiquitous wood-based products used in flat-pack furniture and for interior cupboards and work surfaces (finished with HPL). It is also used for wall and floor panels.

Table 2.3 Classification of particleboard according to EN 312 (CEN, 2010)

Classification	Use
P1	General board for use in dry areas
P2	Non-structural board (including furniture) for use in dry areas
P3	Non-structural board for use in dry or humid areas
P4	Load-bearing boards for use in dry areas
P5	Load-bearing board for use in dry or humid areas
P6	Heavy-duty load-bearing board for use in dry areas
P7	Heavy-duty board for use in dry or humid areas
P8	Extra heavy-duty board for use in dry areas

2.4.3 Oriented strand board

OSB is a panel made of strands (also called flakes or wafers) of wood, rather than the particles used in particle board. The strands have an approximate size range of 15–25 mm wide, by 75–50 mm long, by 0.3–0.7 mm thick, and when used, they are aligned usually along the long axis of the board. OSB is a recently modern development, being used in the United States in the 1960s and the Europe in the 1970s but has since progressed to take a majority share of the structural panel market (at the expense of plywood) (Stark *et al.*, 2010).

Manufacture. The manufacture of OSB involves the debarking and flaking of round wood logs usually taken from fast growing species, such as pine or aspen. Spruce, hemlock, poplar and maple are also relatively common. In theory, any timber species could be used though the actual use is dependent on availability and cost. Other non-wood-based lignocellulose materials, for example, bagasse (Silva *et al.*, 2012) and straw (Cheng *et al.*, 2013), have also been researched. The strands produced are then dried and screened to remove the smallest flakes, before blending with a resin, which is usually a MUF or PF type (3%–8% range), although other resins have also been used. Wax (<1%) may also be added to improve the properties of the panel. A continuous mat of strands is then formed, usually in three layers with the surface layers oriented along the axis of the board and the core perpendicular to the long axis. The mat is cut and pressed at high temperature (200–220°C) before finishing. Tongue and groove joints would be formed in the board at this point (for a detailed description, see Thoemen *et al.*, 2010; Nishimura, 2015).

Properties. OSB has good strength properties and is comparable with plywood, though it has a generally higher shear strength. It can take fastenings, such as nails, well and has reasonable durability against biological attack (Wood Panels Industry Federation, 2014c). It is, however, more hygroscopic than plywood, and its performance (depending on grade) is generally worse than plywood. As an engineered wood products, it shows uniformity of properties and is generally free of defects, such as knots (Wood Panels Industry Federation, 2014c). It can be coated, stained or painted to improve its aesthetic qualities and can be treated with fire retardants or preservatives. In Europe, OSB is classified according to standard EN 300 (CEN, 2006) as summarised in Table 2.4.

Applications. OSB is widely used as a structural wood panel for floors (including subfloors and underlays), walls and ceilings. It is used for interior fittings, furniture, shuttering and packaging and also in the manufacture of I-joists, where it forms the

Table 2.4 Classification of OSB according to EN 300 (CEN, 2006)

Classification	Use
OSB/1	Boards for general purpose use and interior use in dry conditions
OSB/2	Boards for load bearing in dry conditions
OSB/3	Boards for load bearing in wet/moist conditions
OSB/4	High-specification boards for load bearing in wet/moist conditions

web or support between two flanges of solid wood. OSB is being used not only for its structural properties but also for its aesthetic value, with some designers using it as an interior design feature.

2.4.4 Fibreboard

Fibreboards are a group of similar products that are constructed using wood that has been reduced to a fibrous state. There are two main processes used to classify the types of boards, the 'wet' process used to manufacture SB and HB without glue and the 'dry' process used to manufacture products such as MDF using adhesive resin. The first fibre-based board factory was set up in Sunbury-on-Thames, England, in 1898, making half hard fibreboard, by 'The Patent Impermeable Millboard Company' (Kollman *et al.*, 1975). Modern HB was developed and patented as Masonite in 1924 by William Mason (Baird and Schwarzt, 1956), whilst MDF, as produced today, was not developed until 1965 in the United States. Of the various products, MDF (produced from the 'dry' process) has the greater market share.

Manufacture. SB (200–400 kg/m^3) and HB (>900 kg/m^3) are produced using fibres obtained from round wood logs. The logs are debarked, chipped steamed and then refined through metal plate defibrator to produce wood fibres. The fibres (2% in wt) are washed and mixed with water in tanks to form a pulp. Small amounts (<1%) of additives and wax are added to decrease swelling and water absorption. The pulp is then fed onto a moving mesh belt where it is pressed between rollers with vacuum applied to drain off the water. The SB panel is then dried in roll dryer (see also Thoemen *et al.*, 2010 or Ormondroyd and Stefanowski, 2015, for a more detailed explanation).

In HB manufacture, the felt is hot-pressed to remove the large quantities of water and form the dense HB panel. The panel is finished off by cutting and trimming. Due to the mesh used, the panel will have a smooth top surface and a rougher mesh bottom surface. The HB can be tempered by oil impregnation to improve its properties (Kollman *et al.*, 1975).

MDF is also produced from fibres derived from fresh (usually softwood) or recycled wood. The wood is chipped and washed before being placed into a digester. Here, the fibres are exposed to steam at 0.6–1 MPa pressure before being refined through metal plates. The fibres are then mixed with resins (10%–14%), wax (<1%) and any other additives before drying in high-speed 'flash' dryers. The fibres are formed into a flat mat and hot pressed (180–210°C and 0.5–5.0 MPa). The time and pressure is altered to obtain panels of varying density. The panels are finished by sanding to obtain smooth surfaces. The use of waste or low-value materials in production has been investigated as a means of reducing costs and adding value to waste streams, without reducing the characteristics of the material. For a detailed description of the process, see Thoemen et al. (2010) or Ormondroyd and Stefanowski (2015).

Properties. SB has good heat insulation properties with thermal conductivity 0.045–0.05 W/mK, and sound insulation 22 dB. In Fig. 2.23, wind-barrier boards with tongue and groove joints can be seen on the left and parquet underlay (on top) with standard and wind protection board on the right. SB is classified in Europe by EN 622-4 (CEN, 2009a).

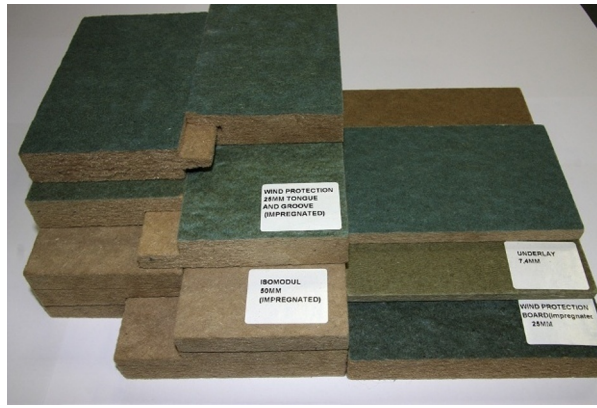


Fig. 2.23 Softboards used for insulation and wind protection applications.

Table 2.5 Classification of hardboards according to EN 622-1 (CEN, 2003c)

EN 622 classification	Use
HB	General purpose board for dry conditions
HB.H	General purpose board for humid conditions
HB.E	General purpose board for exterior use
HB.LA	Load-bearing board for dry conditions
HB.HLA1	Load-bearing board for humid conditions
HB.HLA2	Heavy-duty load-bearing board for humid conditions

HB shows good strength properties and a high strength-to-weight ratio (Wood Panels Industry Federation, 2014d). It can be susceptible to water unless tempered. Tempering also increases the resistance to dents and scratches. In Europe, HB is classified by the standard EN 622-2 (CEN, 2004) based on the use and environment (Table 2.5).

MDF is, by its nature, a uniform product. This allows it to be machined into complicated shapes without splintering or breaking and can be edged profiled with good results. It can be embossed, painted or coated easily. However, it does have low resistance to moisture, mostly due to the use of UF resins (often a financial factor), limiting it predominantly to indoor use unless moisture-resistant resins are used. The low moisture resistance also makes it susceptible to biological attack by decay fungi. One use issue with working with MDF is the dust caused; this may be harmful if the proper precautions, such as proper ventilation, are not used. In Europe, MDF is classified for use by the standard EN 622-5 (Table 2.6) (CEN, 2009b) (light and ultralight MDF are also classified by EN 622-5 for general (non-load-bearing) use).

MDF is also a very good base for veneers, coatings and paints increasing its use in decorative and artistic situations (Wood Panels Industry Federation, 2014e).

Applications. SB is used as wind-barrier material under cladding, internal sound insulation material and durable underlay for parquet. HB is used in furniture and

Table 2.6 Classification of MDF according to EN622-5 (CEN, 2009b)

EN 622 classification	Use
MDF	General purpose board for dry conditions
MDF.H	General purpose board for humid conditions
MDF.LA	Load-bearing boards for dry conditions
MDF.HLS	Load-bearing boards for humid conditions
MDF.RWH	Board for rigid underlays in roofs and walls

residential and commercial fittings, as well as floor coverings. Untempered HB is not suitable for exterior use due to its poor moisture resistance.

MDF is very versatile and is widely used for shop fronts, signs, displays, fittings, mouldings, architraves and facades. It is also used in flooring, although that is increasingly using a higher density version of MDF called high-density fibreboard (*HDF*) that as the name suggests, has a higher density to increase impact resistance.

2.4.5 Other panel types

There are other types of panels that are used but in much lower quantities than the main types, and these are briefly mentioned as follows:

- *Blockboard*—similar to plywood but formed from softwood strips ~25 mm wide, where the grain of adjacent strips are perpendicular to each other. This type of board is cheaper than plywood but has poor moisture resistance and is usually only intended for interior use.
- *Battenboard*—another variation on plywood with wider strips than blockboard, making it cheaper. Again, it is normally used for interior purposes, such as shop fittings.
- *Laminboard*—a higher quality version of blockboard that uses veneers glued at right angles to each other to give a strong product.
- *Mediumboards* are fibreboards manufactured using the wet process but with a higher density than SB but lower than HB. Their main use is internal fittings and as acoustic baffling.
- *Cement boards*—these are made from wood particles or strands encased in cement. They are durable, resistant to biological attack from fungi and termites and fire-resistant. However, they are not suitable for load-bearing structural uses (Stark *et al.*, 2010) and are very heavy.
- *Recycled boards*—high-pressure boards from recycled wood and thermoplastics. These include recycled MDF boards such as those being developed by MDF recovery limited in the United Kingdom (Bartlett, 2015).
- *Valchromat*—these are boards made of coloured wood fibres bonded with low formaldehyde emission glue and are more dense and stronger than MDF.

2.4.6 Future directions for panel materials

Development of bio-based panel materials faces a number of challenges, both presently and in the future, including financial, material and environmental concerns. There are always commercial concerns in reducing costs and technical innovation in production machinery and processing to increase efficiency, and energy use is one possible approach. Development of the panel products themselves is another approach; the

use of different materials such as renewable fibres crops, for example, bagasse (Silva *et al.*, 2012), cotton (Pandey *et al.*, 2011) and straw (Cheng *et al.*, 2013), is seen as both financially and environmentally beneficial. Incorporation of waste products has also been investigated, with varying results, to produce products able to fill part of the spectrum of panel types and grades, for example, waste paper (Grigoriou, 2003), papermaking residues (Davis *et al.*, 2003; Geng *et al.*, 2007; Migneault *et al.*, 2010), paper recycling residues (Curling *et al.*, 2016), rice husks (Pandey *et al.*, 2011) and pine cones (Kose *et al.*, 2011). Treatment of the substrates, for example, wood modification by acetylation (Papadopoulos and Traboulay, 2002; Mohebby *et al.*, 2009) or thermal methods (Candan *et al.*, 2012), has also been used as a method of improving the panel properties.

There is a drive to improve the resins used in panel products for financial; performance, for example, increased moisture resistance; and, probably most importantly, environmental reasons. One of the main environmental concerns is the use of formaldehyde-based resins; for though there are many sources of formaldehyde in the indoor environment, aside from the panel products, formaldehyde has been identified as a possible harmful chemical, prompting some concern. Development of the resins system has progressed rapidly from using low emission to low or non-formaldehyde resins, for example, those based on cornstarch tannins or lignin (Ballerini *et al.*, 2005; Despres *et al.*, 2010, Moubarik *et al.*, 2010, Pizzi *et al.*, 2011), and now, potentially to using panels products, such as MDF, to remove formaldehyde from indoor air that was released from other sources (Stefanowski *et al.*, 2015).

End-of-life scenarios for panel products other than landfill or burning are also being investigated with methods and approaches for recycling panel products into new materials and panels being developed (Bartlett, 2015; Shalbafan *et al.*, 2016).

The increasing use of modular structural insulated panels is becoming more financially and commercially feasible. These modular units are preformed in a factory setting and utilise wood panels as part of their construction (Mullens and Arif, 2006; Uddin and Kalyankar, 2011). This type of construction product promises new roles and requirements for panel materials in the future.

2.5 Wood plastic composites

G.A. Ormondroyd[*,†], *J. Kers*[‡]
[*]Bangor University, Bangor, United Kingdom
[†]University of Bath, Bath,United Kingdom
[‡]Tallinn University of Technology, Tallinn, Estonia

2.5.1 Introduction

Wood plastic composites (WPCs) are composites manufactured from predominantly (typically synthetic) thermoplastic resins and wood flour filler, though thermoset resins and naturally derived resin systems may also be used. WPCs have been developed over

the last 40 years, and their application areas have expanded to both structural and non-structural applications (Schwarzkopf and Burnard, 2016). WPC production is now regarded as one of the most dynamic and fast-growing sectors of the wood industry (Asif, 2009). The trend in production of WPC is positive and rising, 220,000 tonnes were produced in Europe in 2010, and this capacity rose to 260,000 in 2012 (Spear and Eder, 2015; Schwarzkopf and Burnard, 2016). US demand for WPC and plastic lumber products is forecast to advance 6.9% per year to $5.9 billion in 2020 (Freedonia/Fordaq, 2016). The use of WPCs can be found in many sectors including garden and yard products, packaging, consumer good; however, the major growth sectors, worldwide, are automotive and construction products (La Mantia and Morreale, 2011; Eder and Carus, 2013).

WPC production is fairly straightforward. A flour of wood or woody biomass is blended with a polymer, usually polyethylene or polypropylene in an extruder. The product is then either extruded in to pellets for storage and reprocessing or extruded in to complex WPC product shapes for final applications.

The earliest developments of WPCs date back to the 1970s with Gruppo Ovattifici Riuniti (*GOR*) producing a product named 'Woodstock' for Fiat in 1972 and Sonesson AB producing a *PVC*/wood-flour composite for use as flooring tiles in 1973 (Schwarzkopf and Burnard, 2016). Whilst the concept of WPCs is fairly straightforward, research has continued from the 1970s to the present day with research focusing on the improving the compatibility of the two components, the use of novel filler materials and the reduction in density. The development of WPCs has also coincided with the developments of biopolymers, and this has lead to a considerable crossover between the two disciplines, which has lead to the development of 100% bioderived products; however, such products bio-based WPC would be cost-prohibitive and typically only occupy niche markets (Spear and Eder, 2015; Zierdt *et al.*, 2015).

2.5.2 The components of WPCs

The matrix. As mentioned earlier in the section, WPCs are generally manufactured from thermoplastics. Thermoplastics are polymers that can be heated, formed, cooled and hardened and then reheated and reformed. This allows the WPC to be moldable and for complex shapes to be developed. The use of thermoplastics also allows for recycling of the composites to take place with relative ease. When thermoplastics are processed, they do not rely on cross-linking to develop the solid matrix, rather on the intrinsic properties of the monomers, the large molecular weights and polymer entanglement (Hull and Clyne, 1996). When heated, the polymers disentangle and allow for reprocessing of the composite.

Many thermoplastics are used in the manufacture of WPCs; however, the major proportion of the market is accounted for by three major polymers, polyethylene (*PE*), polypropylene (*PP*) and polyvinyl chloride (PVC). Polyethylene (both low density and high density) is used across the European market, whilst PVC wood composites have found a market within the United States for window framing. Other polymer composites are beginning to hit the market; for example, Evonik has recently released a composite based on polyethylmethacrylate (*PMMA*). The product 'Mydeck' requires a unique extrusion process and creates a product that is said to resemble varnished wood (Spear and Eder, 2015).

Thermoset resins have been used historically for the manufacture of wood-polymer composites. They are resins that cure from a liquid state to a solid through a non-reversible cross-linking reaction. Formaldehyde-based resins are common throughout the wood panel industry and have been used along with polyamides and epoxys for the manufacture of durable WPCs. Interestingly, the first WPC produced was a PF wood-composite-branded Bakelite and produced by the Rolls Royce company in 1916 (Clemons, 2002). Thermoset resins are applied as adhesive or matrix material for flexural and tension strengthening of timber beams with carbon-, basalt- and glass-fibre-reinforced laminate layers (Fernando *et al.*, 2016; Khelifa *et al.*, 2015).

To increase the mechanical strength of the WPC, the material can be increased with continuous glass fibre reinforcements impregnated by using epoxy adhesives as bonding agents on external surfaces or as embedded and impregnated rovings inside the WPC profile cross section (Zolfaghari *et al.*, 2013).

As mentioned earlier, the recent developments in the WPC industry have coincided with the development of biopolymers (Zierdt *et al.*, 2015). As the development of biopolymers and perhaps more importantly as production, capacity of biopolymers has increased the development of their composites with wood has been steadily researched and developed (Teuber *et al.*, 2016; Reddy *et al.*, 2013; Satyanarayana *et al.*, 2009; Yu *et al.*, 2006; Zierdt *et al.*, 2015). Various biopolymers have been used experimentally in the production of WPC; however, the most suitable polymers for the industry are polylactic acid (*PLA*) and polyhydroxyalkanoates (*PHA*) and their derivatives. These biopolymers are considered suitable due to their availability and their melting points.

Whilst biodegradable WPCs have been researched and produced for short- and medium-term applications, they are not applicable to the construction industry and therefore not covered in this chapter.

Wood fibre and fillers. The use of fillers in the polymer industry is nothing new, minerals such as talc and calcium carbonate and synthetic materials such as glass, basalt and carbon fibres have been used as reinforcing materials (Wua *et al.*, 2014; Zolfaghari *et al.*, 2013). Glass fibre-reinforced recycled mixed plastic waste composites can replace chemically treated wood in large-scale outdoor applications such as railroad crossties and bridges, but their mechanical behaviour at elevated temperatures and UV rays needs further study (Bajracharya *et al.*, 2014). On the other hand, wood has been used in non-polymer composites for construction for many years. For instance, wood-cement composites have been used in the fabrication of buildings since the early 1900s (Wolfe and Gjinolli, 1996).

Wood flour obtained by milling technology is classified (Klyosov, 2007) into four factions by size (50–150, 100–200, 200–450 and 250–700 µm). Wood sawdust has very broad distribution by particle size 20–5000 µm and is obtained as by-product in wood cutting by saw. Examples of black alder (*Alnus glutinosa*) wood waste milled with disintegrator milling device into different fraction size are presented in Fig. 2.24 (Kallakas *et al.*, 2015).

Wood has advantages over the traditional fillers for polymer composites, and these include cost, strength-to-weight ratio and low density. English et al. (1996) found that wood flour gave similar properties to talc and other mineral fillers whilst having a lower specific gravity and therefore producing lighter composites.

Fig. 2.24 Examples of black alder (*Alnus glutinosa*) wood waste crushed and milled into different fraction sizes (from left), shavings 4–8 cm, preliminary crushed 2–4 cm and refined to particles 0.63–1.2 mm and <0.63 mm.

The species of timber used in the manufacture of WPCs is typically determined by geographical location, availability and price (Schwarzkopf and Burnard, 2016); however, the species selection does affect the final product by influencing the chemical compatibility of the fibres to the polymer and the mechanical properties of the final product through differing fibre geometries. Berger and Stark (1997) assessed several species for their compatibility with polymers and found that hardwoods fibre gave composites with better flexural and heat deflection properties.

Whilst there has been some research in to the use of postindustrial and postconsumer waste wood in the manufacture of WPCs (Chaharmahali *et al.*, 2010; Nourbakhsh *et al.*, 2010), much has centred on the use of clean wood residues (such as saw dust and planar residues) as a source of fibre. Spear and Eder (2015) noted that the mechanical data found for postconsumer sawdust WPC by Chaharmahali *et al.* (2010) are comparable with the figures found for uncompatibilised virgin WPCs. However, it has been noted that the research into the use of waste wood has been eclipsed by the research into the use of postconsumer plastics and recycled particle board (Ormondroyd *et al.*, 2016; Sommerhuber *et al.*, 2016). Use of waste plastics in WPCs has a great potential, on the other hand due to repeated thermal processing cycles and degradation of the polymers during environmental exposure may show different mechanical properties and performance compared with virgin ones (Najafi, 2013).

The particle size and geometry of the wood filler can have a great influence on the properties of the composite. Generally, when the wood is milled in an industrial setting, the particle size distribution is wide. Stark and Rowlands (2003) assessed the effects of particle size on the final composite properties. The general conclusions were that the finer the powder, the less stress concentrations the composites exhibited when under impact loading. However, it should also be noted that the aspect ratio of the particle (or fibre) will have an effect on the properties of the composite with a larger aspect ratio leading to better stress transfer between the matrix and the fibre (Schwarzkopf and Muszynski, 2015).

A recent development in WPC is the use of paper mill primary sludge rather than virgin wood fibre. The primary sludge contains a higher cellulose content and longer fibres with better integrity and thus higher reinforcement than secondary sludge fibres. The WPC reinforced with kraft sludge fibres had the best mechanical properties followed by chemothermomechanical pulp (*CTMP*) fibres and thermomechanical pulp (*TMP*) fibres (Soucy *et al.*, 2014).

2.5.3 The manufacturing process

Compounding. The compounding of the polymer and the fibre together is a critical step in the manufacture of WPCs. It is essential that the fibres are evenly distributed throughout the polymer matrix to give the final product uniform properties. The dispersion of the fibres becomes increasingly important with the increased fibre content. If the components of the composite are compounded together correctly, this will allow for the fibre to be wetted out with the polymer, and this will in turn lead to better load transfer in the final product.

Extrusion is by far the most common forming step in the manufacture of WPCs. The compounded polymer is remelted and then fed through an extruder die to form the profile that is needed for the desired product. The extruded material is then fed into a cooling bath before being cut to the desired length. A twin screw extruder can be used to recompound the pellets with additional additives prior to extrusion.

The extrusion process produces a linear product with a 2D profile. There are two main types of WPC extruded profiles, hollow profiles and solid profiles (see Fig. 2.25). UPM ProFi product (see Fig. 2.25 left) containing 50% of recycled paper and 50 wt% of plastic and additives is virtually lignin-free and contains no harmful chemicals (UPM ProFi, 2016a,b). Surface finishing of the extruded profiles can be directly from the mould, sanded after extrusion (see Fig. 2.25 in the middle) or laminated with different textures after extrusion. Relazzo Terra by Rehau hollow and solid profiles (see Fig. 2.25 in the middle) is containing 50 wt% of virgin plastic and 50 wt% of wood fibres. WPC profiles are produced in China from recycled plastics and additives 40–50 wt% and wood fibres 50–60 wt% (see Fig. 2.25 on the right).

This makes extruded products readily interchangeable with moulded timber products, such as decking boards, siding, facades, fencing, planks and packaging applications. The advantage of extrusion over other moulding techniques is that it is a continuous process and the manufacturing of product is time and labour economic.

Direct extrusion of thin-wall hollow WPC window profile was firstly made by Schut (2007), and recent developments in 2015 by Austrian company Zitta (see Fig. 2.26) are using PVC plastic matrix with additives 50 wt% and fine fraction of wood flour <50 µm about 50 wt%.

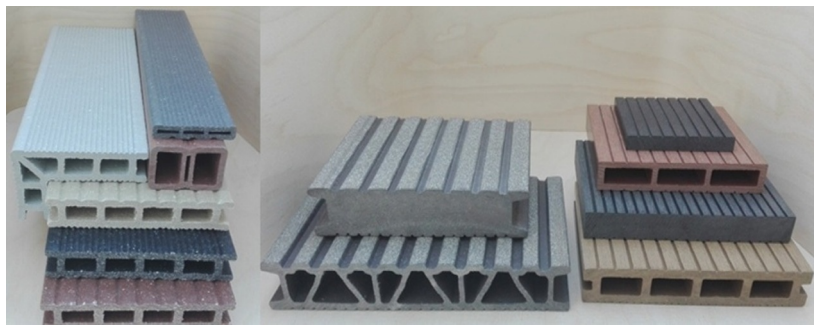


Fig. 2.25 Different WPC profiles from producers (left) UPM ProFi, Relazzo Terra by Rehau hollow and solid profiles in the middle and WPC profiles produced in China from recycled plastics and wood on the right.

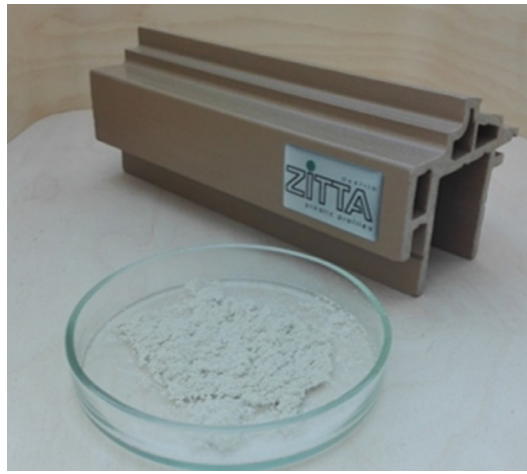


Fig. 2.26 WPC window profile by Zitta.

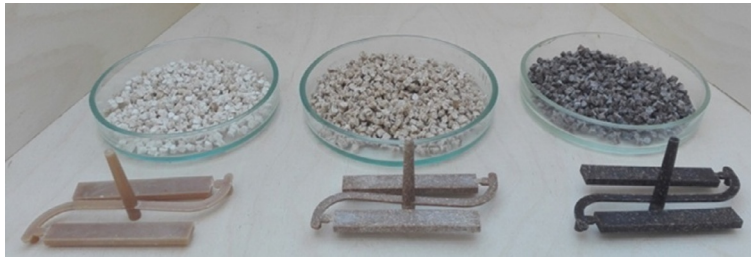


Fig. 2.27 Examples of different WPC mixtures (plastic matrix 65% and wood fibres 35%) and injection-moulded specimens for flexural properties (from left), bleached chemi-thermomechanical pulp from Aspen (*Populus tremula*) and polypropylene (PP) (left), birch (*Betula*) wood waste and PP (middle) and alder (*Alnus incana*) wood waste and PP (right).

Injection moulding. Whilst extrusion is by far the most common moulding technique for WPC, injection moulding can be used to form complex three-dimensional shapes. Injection moulding is similar to extrusion in that the polymer/wood pellets are remelted but are then fed in to a mould rather than through a die. The die is then cooled, and the component is then ejected. Through the very nature of the production cycle, the manufacture of injection-moulded components is a batch process, and therefore, there needs to be a large investment into the tooling to make the manufacturing cycle economical. Injection moulding is used for items such as plant pots, speaker housing and radiator grills. Examples of different WPC mixtures and injection moulded specimens are presented in Fig. 2.27 (Kallakas *et al.*, 2015).

2.5.4 Wood polymer composites in the construction sector

WPCs are used extensively in the built environment, and the linearity of the products lends itself to the production of substitute products to those manufactured from solid

Fig. 2.28 Hollow WPC profiles before the three-point flexural test ISO 16616 (ISO, 2015) on the left and after test on the right.

wood and pure polymers. A recent study by Osburg *et al.* (2016) on the consumer acceptance of WPCs in relation to competing materials showed that a higher level of environmental concern and the innovativeness of the consumers towards new materials lead to more WPCs being accepted.

To increase credibility for potential application areas for WPC in the construction sector (i.e. for cladding and facade materials), the bending strength (see Fig. 2.28), the fire-resistance properties, fungal decay and UV-degradation properties need to be improved (Naumann *et al.*, 2012).

By far, the most common WPC product within the built environment is decking, with the substitution of solid wood being due to the reduced maintenance cost (i.e. it does not need to be retreated). However, other products are now been seen on the market, these include railing, stairs, windows, doors, flooring, cladding fencing, interior moulding and trim work (Clemons, 2002; Klyosov, 2007; Eder and Carus, 2013; Carus *et al.*, 2015; Schwarzkopf and Burnard, 2016). This substitution again is generally a substitution for solid wood and is due to a reduced maintenance schedule for the products and the building as a whole. The flammability properties of WPCs should be improved with flame retardants to widen their use in construction sector (Kim and Pal, 2011).

2.5.5 Performance of the wood polymer composites

The strength properties in microstructural level of WPC products are determined by wood fibre and polymer interfacial bond. The compatibilisers are used to improve the adhesion between hydrophilic wood fibres and hydrophobic polymer matrix for enhancement of strength properties (Olakanmi and Strydom, 2016). The intrinsic properties of the composite can be improved by the use of wood fibres due to their higher aspect ratio of the reinforcement than that of wood flour particles (Stark and Rowlands, 2003). However, there is a technological issue with feeding discrete wood fibres in extrusion or injection moulding process to maintain the fibre length, avoid thermal degradation and ensure orientation and dispersion of the reinforcement in the final product. In the macroscopic level, the design of the profile cross section is most important for strength properties (Ballerini *et al.*, 2008; Schut, 2007). Performance of the

WPC in external conditions concerns the fungi-resistant, colour-retardant and flammability properties, which can be improved with additives (Kim and Pal, 2011). Flame retardants like ammonium polyphosphate and pentaerythritol are decreasing the initial temperature of thermal degradation and promoting char formation but on the other hand reducing the Izod impact or tensile strength of WPC (Li and He, 2004). The limit of mechanical recycling of WPC is recognised due to matrix polymer degradation in repeated heat treatment cycles (Najafi, 2013) and reduction of mechanical properties of the composite due to size reduction of wood fibres (Olakanmi and Strydom, 2016). The 100% biodegradable natural fibre-reinforced composite solutions with biopolymers from biomass (protein, lipids and polysaccharide), polylactid acid, PLA blends and PHA are point of great interest in the near future, but their blending and processing need enhancement, and the cost needs reduction to make them compatible with polyolefine matrix-based composites (Bugnicourt *et al.*, 2014; Sherman, 2008).

2.6 Cellulose, pulp and paper

C.-M. Popescu, D. Jones*[†,‡,§]

*Petru Poni Institute of Macromolecular Chemistry of the Romanian Academy, Iasi, Romania

[†]DJ Timber Consultancy plc, Neath, United Kingdom

[‡]University of Primorska, Koper, Slovenia

[§]Luleå University of Technology, Skellefteå, Sweden

2.6.1 Introduction

Wood and plant fibres represent highly complex organic matrices comprising three main components, cellulose, hemicellulose and lignin, along with a small percentage of low molecular compounds. Cellulose molecules are arranged regularly (determining the framework of the cell wall) and are surrounded by hemicelluloses and lignin. The structure of the plant cell wall is compact, existing different bonding amongst the components. The ratio of the components in the cell wall is about 4:3:3 (cellulose/hemicelluloses/lignin) but differs between the sources (i.e. hardwood, softwood and annual plants) (Chen, 2014).

2.6.2 Cellulose

Cellulose, one of the main cell wall components of natural plant fibres, is the most abundant organic matter produced by living organisms. The fine structure of native cellulose fibres has important implications in the biological processes of plant growth, chemical or enzymatic transformation of cellulosic biomass and for the conception of new material and understanding of physical properties of a wide range of cellulose-based materials (Nishiyama, 2009). Land plants (such as forest trees and cotton) synthesise cellulose from glucose which is produced in the plant cells by photosynthesis. Cotton has the highest amount of cellulose (about 90%), followed by bast fibres

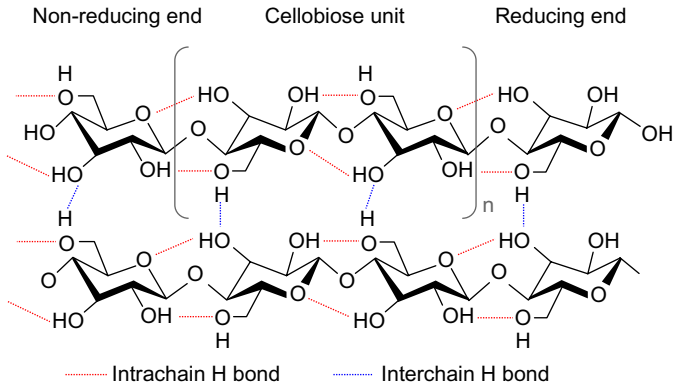


Fig. 2.29 The cellulose polymer chain structure.

(such as flax, hemp or ramie, which have about 70%–80% cellulose content) and wood with about 40%–50% cellulose content (Han and Rowell, 1996).

Unicellular plankton or algae in the ocean also generate cellulose by fixation of carbon dioxide. Cellulose may be also assembled by several animals, fungi and bacteria, which are devoid of photosynthetic ability and require glucose or other organic substrates and are dependent on other organisms.

Structure. Cellulose is a linear syndiotactic polymer consisting of D-anhydroglucopyranose rings ($(C_6H_{10}O_5)_n$). The cellobiose unit (the smallest repeating unit in the polymer) consists of two anhydroglucose units joined through single-oxygen atoms (acetal linkages) between the C1 of one pyranose ring and the C4 of the next ring (1–4 linkage) as shown in Fig. 2.29 (Kalia *et al.*, 2011; Wang *et al.*, 2016; Roy *et al.*, 2009). They are rotated 180 degree with respect one to the other.

The number of *n* repeating units defines the degree of polymerization (DP) of the cellulose, and subsequently, as no polymer is homogenous in length, the molecular weight distribution will influence the fibre properties. Depending on source, the DP might vary considerably. For example, native wood cellulose has n of ~10,000, whilst cotton plant-fibre cellulose is about 15,000 (Moon *et al.*, 2011). After extraction, the DP of cellulose is reduced drastically between 300 and 1700 in wood cellulose, whilst in cotton, other plant fibres and even in bacterial cellulose, the range is about 800–10,000, depending on the applied treatment (Klemm *et al.*, 2005).

The macromolecular chain of cellulose consists of two different ends: at one end a d-glucose unit with a free hydroxyl group at the C4 position (a non-reducing end) and the other end contains a free hemiacetal or aldehyde at the C1 position (reducing end). Each glucose ring presents three hydroxyl groups in different positions: at C6—a primary alcohol and C2 and C3—secondary alcohols (Roy *et al.*, 2009). The hydroxyl groups in the cellulose polymer can form hydrogen bonds within the polymer itself (intramolecular hydrogen bonds) or between different cellulose polymers (intermolecular hydrogen bonds). The intramolecular bonds give stiffness to the polymer chain (Moon *et al.*, 2011), whilst the intermolecular bonds allow the linear polymers to aggregate and form fibres (Kalia *et al.*, 2011). Within these cellulose fibrils, there are regions

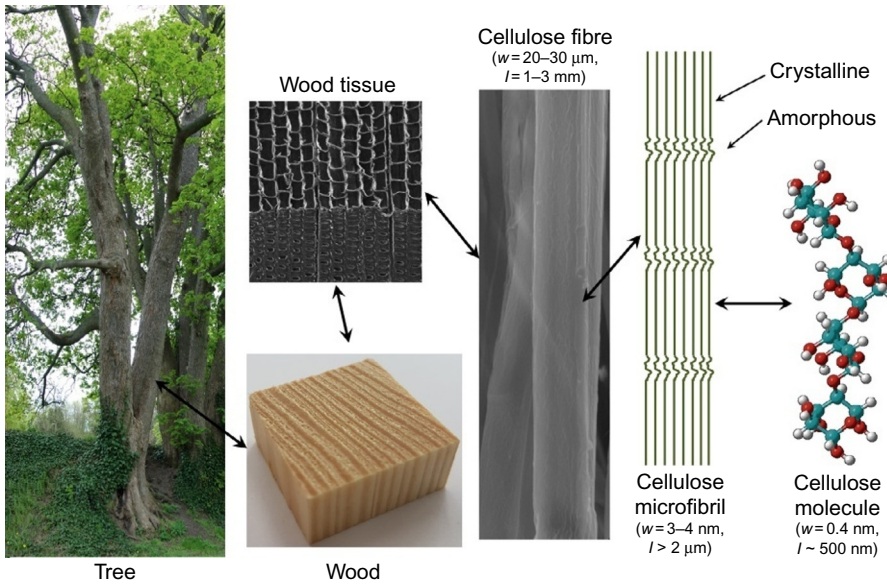


Fig. 2.30 Hierarchical structure of wood and the characteristics of cellulose microfibrils.

where the cellulose chains are arranged in a highly ordered crystalline structure and regions arranged in a low order or amorphous regions (Salas *et al.*, 2014). In the crystalline regions, the interchain hydrogen bonds are strong, providing the resultant fibre good strength, high axial stiffness, insolubility in most solvents and prevent cellulose from melting (non-thermoplastic). In amorphous regions, the chains are further apart, making them more amenable to hydrogen bonding with other molecules (i.e. water).

The structure of a cellulose fibre can be divided into three different levels, the molecular level (described above and presented in Fig. 2.29), the supramolecular level (the polymer chains ordered in crystalline and non-crystalline regions due to hydrogen bonds—Fig. 2.30) and the morphological level (the cellulose fibre aggregated to form microfibrils and further—macrofibrils oriented in different layers in the cell wall—Fig. 2.30). The natural strength and stiffness of the cellulose fibres result from the formation of the microfibrils.

2.6.3 Pulp and paper

One of the largest industries across the world is the production of pulp and paper. The process is highly cost-sensitive and requires increased productivity and quality, as well as respecting the environmental regulations. Pulp is produced from raw materials (like wood, agricultural residues—cereal straw, bagasse, bamboo, reeds, jute, flax and sisal—and recycled paper) with a different content of cellulose fibres (Bajpai, 2012).

There are several main steps in the manufacturing of the pulp and paper:

- Raw material preparation and handling.
- Pulp manufacturing.

- Pulp washing and screening.
- Chemical recovery.
- Bleaching.
- Stock preparation.
- Papermaking.

The *first step* consists of debarking (if wood is used as raw material), chipping and depithing (if bagasse is used as raw material).

Further, as a *second step*, the cellulosic pulp is obtained from the raw materials by mechanical, thermal and/or chemical processes. By *mechanical pulping*, the fibres are separated by mechanical abrasion, which causes gradual break of the bonds between the fibres and the release of fibre bundles, single fibres and fibre fragments (Bajpai, 2012; Fardim *et al.*, 2012). The major advantage of mechanical pulping is its high yield of fibres—up to 90%. *Chemomechanical pulping* involves mechanical abrasion and the use of chemicals. *Thermomechanical pulps* are manufactured from raw materials by the application of high-temperature steaming, in addition to mechanical processing. *Chemi-thermomechanical pulping* (CTMP) is similar to chemomechanical pulping but uses less mechanical energy and softens the pulp with sodium sulphite, carbonate or hydroxide. This pulp has good strength properties.

Today, the most used process in the world to produce paper commercially is the chemical pulping process (Smook, 1992; Bajpai, 2012; Fardim *et al.*, 2012). *Chemical pulps* are made by cooking the raw materials, using the kraft (sulphate) and sulphite processes. The kraft process is by far the most dominating chemical pulping process worldwide due to its large applicability to different wood raw materials and high strength of pulps in comparison with sulphite cooking (Fardim *et al.*, 2012). In the kraft pulp process, the active cooking chemicals are sodium hydroxide and sodium sulphide. These processes produce a variety of pulps used mostly for high-strength papers, board and packaging. On the other hand, sulphite process uses different chemicals to remove lignin and permits the production of many different types and qualities of pulps for a broad range of applications. It is a good alternative for preparation of dissolving pulp because hemicelluloses are extensively removed when the process is operated under acidic conditions (Potthast, 2006).

The sulphite process can be distinguished according to the pH adjusted into different types of pulping, acid (bi)sulphite, neutral sulphite (*NSSC*) or alkaline sulphite. Chemical pulping yields ~50% but offers higher strength properties, and the fibres are more easily breached.

After the production, pulp is processed by different techniques to remove the impurities and to recycle any residual cooking liquor via the *pulp washing process*. Residual cooking liquor from chemical pulping is washed from the pulp using pulp washers, the so-called brown stock washers (for kraft) and red stock washers (for sulphite). In order to maximise the *chemical recovery* and to minimise carry-over of cooking liquor (known as washing loss) into the bleach plant, efficient washing is critical. If this step is not properly applied, then the excess cooking liquor will increase the consumption of the bleaching chemicals, due to the formation of bindings between them.

The role of *bleaching* is to increase pulp brightness through chemical treatment of unbleached pulp. There are two stages used in this process, removal of the small

fraction of the lignin remaining after cooking (in chemical pulps) and lignin-retaining bleaching (in mechanical pulps). In this process, different chemicals (oxygen, hydrogen peroxide, ozone, peracetic acid, sodium hypochlorite, chlorine dioxide, chlorine, etc.) are used to transform lignin into an alkali-soluble form. More recently, in the first step of bleaching, oxygen is used (Bajpai, 2005, 2012; Fardim *et al.*, 2012) to avoid the chlorine chemicals and employ 'total chlorine-free' bleaching. Generally, the chlorine compounds resulted from the bleaching stages are toxic and are not practical to recover in effluents, since the chloride content causes excessive corrosion.

The next step, before pulp can be transformed in paper, is the stock preparation. This process is dedicated to form macroscopic flocks composed of colloidal particles, filler and pulp fibres and also to modify the surface chemistry of the fibres (Fardim *et al.*, 2012). This step includes blending of different pulps, dilution and the addition of chemicals. The quality of the finished stock determines the properties of the paper produced. Stock preparation consists of several process steps (as fibre disintegration, cleaning, fibre modification, storage and mixing) and depends significantly on the raw stock used and on the quality of furnish required.

Refining is one of the most important operations when preparing papermaking fibres (Baker, 2005; Bajpai, 2005). By this process, different fibre properties for specific grades of paper are obtained. It aims to develop the bonding ability of the fibres without reducing their individual strength by damaging them too much whilst minimising the development of drainage resistance (Bajpai, 2005, 2012). Fibres usually react differently because of dissimilarities in their morphological properties; therefore, this process should take into account the type of fibres. During refining (Baker, 2005; Bajpai, 2005, 2012), the fibres *develop new surfaces externally* through fibrillation and *internally* through fibre wall delamination; *deform*, resulting in changes in their geometric shape and the alignment along their length; and *break*, resulting in changes in length distribution and a decrease in mean fibre length. All these changes occur simultaneously, and the extent of these changes depends on the morphology of the fibres, processing temperature, chemical environment and the treatment conditions.

At the end, the pulp can be treated with different chemical additives—resins (to improve the wet strength of the paper), dyes and pigments (to obtain a desired colour of the sheet), fillers (talc and clay to improve optical qualities) and sizing agents (to control diffusion of liquids and to improve the printing properties) (Hodgson, 1997; Bajpai, 2012).

The last step is to form the slurry (consisting in about 99.5% water and 0.5% pulp fibre) into the desired type of *paper* at the wet end of the paper machine.

Along the machine path, water drains through the mesh, and fibres align in the direction of the wire travel. The excess of water is removed through vacuum boxes. When the paper leaves the press section, the sheet usually has about 65% moisture content. The next step uses the steam-heated dryers, which will evaporate the water. If the paper will undergo a sizing or coating process, then a second drying operation will be performed. A moisture content of about 4%–6% is required.

At the end of the paper machine, paper continues onto a reel for winding to the desired roll diameter. For the paper used in the manufacture of corrugated paperboard, the process is completed at this stage. If the paper is used in other purposes, the next

steps are finishing, coating and converting operations, off line from the paper machine. Other operations can also take place including cutting, sorting, counting and packaging (Bajpai, 2012).

2.6.4 Cellulose, pulp and paper properties

The cellulose properties are influenced by the isolation process, the number of inter- and intramolecular hydrogen bonds, the chain length and distribution and its crystallinity. The molecular structure of cellulose, which is responsible for its supramolecular structure, determines many of its chemical and physical properties.

The cellulose fibres present high strength and durability. The mechanical properties depend on the cellulose type, due to each cellulose type having its own geometry (Heinze, 2016). Depending on the fibre isolation procedure, either natural fibre or pure cellulose fibre can be tested by using the single-wood fibre approach.

2.6.4.1 Physical properties

The hydroxyl groups present on cellulose backbone and their ability to make hydrogen bonds between cellulose chains govern the physical properties of cellulose.

The intra- and interchain hydrogen bonding between hydroxyl groups and oxygens of the adjoining ring molecules makes cellulose a relative stable polymer and gives the cellulose fibrils high-axial stiffness. Hydrogen bonding within neighbouring cellulose chains may act to determine the straightness of the chain and impart improved mechanical properties and thermal stability to the cellulose fibres. Interchain hydrogen bonds might introduce order or disorder into the system depending on their regularity (Poletto *et al.*, 2013; Moon *et al.*, 2011).

In dry state, cellulose presents thermosetting behaviour—forming permanent bonded structures that are not broken by simple heat or common solvents without causing chemical decomposition. This behaviour arises from strong dipolar attractions that exist between cellulose molecules, therefore giving it properties similar to those of interlinked polymer networks.

The hydroxyl groups from the cellulose structure undergo strong attractions to a wide range of solvents and solutions. In the sorption process, some of the existing hydrogen bonds in cellulose are broken and replaced by hydrogen bonds formed between cellulose molecules and water or solvent molecules (Chen, 2014). The reversible process (desorption) is much slower resulting the hysteresis. The water in cellulose is found into two states: the so-called bonded water that induces cellulose swelling and generates the heat effect and the free water and the water molecules that are present in the pores and form a main layer of adsorbed water or capillary water. In this state, it is not causing any cellulose swelling. Further, cellulose swellability is divided into swellability in the crystalline regions and swellability between crystalline regions. In the first one, the swelling agent reaches only the surface of the crystalline and amorphous regions, whilst in the second one, the crystalline regions are penetrated by the swelling agent and generate their swelling. Even in the wet state, natural cellulose fibres show almost no loss in strength.

Unlimited swelling of the cellulose is *dissolution*. Using alkali to impregnate celluloses is also called *mercerisation*, when it forms the so-called cellulose II. The alkalisation of cellulose is important to commercial-scale cellulose production as a method for increasing the reactivity of subsequent reactions and for the mercerisation of cotton. The alkali cellulose is also the intermediate product for the production of viscose fibres and derivatives of cellulose ether (Klemm *et al.*, 2005).

Cellulose is insoluble in water, dilute acidic solutions and dilute alkaline solutions at normal temperatures. The cellulose solvents are usually divided into two categories, aqueous and non-aqueous. Aqueous solvents may include inorganic acids (which lead to the homogeneous hydrolysis of cellulose), Lewis acids (which dissolve celluloses with a low DP), inorganic bases (which dissolve cellulose with a low DP), organic bases or complexes. The non-aqueous solvents of cellulose are based on the organic solvents and can be used as a component of the active agent and as a solvent of the activator, which can make the solvent have a larger polarity to dissolve cellulose, producing artificial fibres and films and also cellulose derivatives (Chen, 2014). In the last decade, ionic liquids have emerged as effective and green solvents, mainly due to their high thermal and chemical stability, non-flammable nature and miscibility with many other solvent systems (Isik *et al.*, 2014).

Thermal decomposition of cellulose usually takes place in a narrow temperature interval of 300–375°C. At lower temperatures, dehydration of cellulose takes place forming dewatered cellulose and then charcoal and gas products. At higher temperatures, cellulose decomposes into flammable volatile products (tar). The most important intermediate product of cellulose high-temperature thermal degradation is levoglucosan, which is further degraded to low molecular and tar-like products. The later ones can be polymerised into an aromatic ring structure similar to graphite structure.

The *mechanical properties* of cellulose fibres have been found to be inferior to their synthetic counterparts; however, the properties such as lower densities, good specific modulus values and natural fibres can be highly preferable to synthetic fibres in applications where stiffness and weight are primary concerns (Thakur and Thakur, 2014).

2.6.4.2 Chemical properties

The chemical reactions of cellulose are influenced by its polymorphic nature. The less ordered (amorphous) regions are more reactive than the more highly ordered crystalline regions; the chemical reaction taking place first on the less ordered surfaces of the fibrils and little or no effect is observed on the crystalline structure.

The reactivity of cellulose is, therefore, dependent upon the source and the conditions of isolation and purification (Alistair, 1995; Saheb and Jog, 1999).

The *accessibility* of cellulose refers to the ability of the reagents to reach the free hydroxyl groups. Because of the smallest steric hindrance, the reactivity of the primary hydroxyl groups is higher than for the secondary hydroxyl groups, so the reactivity of hydroxyl at C6 with a bulky substituting group is higher.

The *degradation* of cellulose is an important reaction to produce cellulose products. Acid degradation, microbial degradation and alkaline degradation are used to break the glycosidic bonds between two adjacent glucose units; an alkali-peeling

reaction and oxidation-reduction reaction of cellulose usually act on reducing ends of celluloses, and the oxidative degradation of the cellulose occurs mainly in dissociating hydroxyls at C2, C3 and C6 of the glucosyl ring. Cellulose molecule chains will form carbonyls at C2 when oxidised to some degree and then be degraded in the following alkali treatment process by the elimination reaction of β-alkoxy groups. After disconnecting the glycosidic bond, the reaction product is formed and then degraded to a series of organic acids (Alistair, 1995; Saheb and Jog, 1999).

The *esterification* and *etherification* reactions of cellulose act on three alcoholic hydroxyls of cellulose molecule monomer producing different cellulose derivatives like sulphonic ester, cellulose acetate, cellulose nitrate and cellulose ether (carboxyl methyl cellulose, methyl cellulose and ethyl cellulose).

Sometimes, in order to enhance the reactivity of ester/ether bond of cellulose in multiphase medium and improve the quality of cellulose ester/ether, some pretreatments may be performed. From these, preswelling treatment of cellulose can be used to reduce the hydroxyl-binding forces between cellulose molecules and increase the reagents diffusion velocity (Saheb and Jog, 1999).

Cellulose derivatives with a high degree of substitution can reduce the water absorbability, whilst some cellulose derivatives with a low degree of substitution may have higher water absorbability, degree of hydrolysis and wrinkle resistance. The improvement of wrinkle-resistant property can be used to enhance the stiffness and moisture resistance of cardboard; also, it can improve the burst strength and the dimensional stability of paper.

2.6.4.3 Cellulose insulation properties and performances

Density and settling. The loose fibre insulation material is determined after the installation (varying between 50 and 90 kg/m^3) in vertical or horizontal applications and depends on the dosage of fire additives (which increase the density linearly), the type of additive having little influence on final density. After installation (after one year), the settling density has been found to be of about 11% (Zaborniak, 1989). Therefore, in order to prevent settling, it is recommended to increase the density by 10% after filling the wall cavity (with a minimum density of 57 kg/m^3).

The dry density of cellulose insulation, for wet spray applications, has been shown to increase linearly with installed moisture content, ranging from 39.6% with 40% moisture content to 71.3 kg/m^3 with 100% moisture content (Lopez Hurtado *et al.*, 2016).

Thermal performance of cellulose insulation can vary slightly depending on manufacturing and method of installation and is comparable with other types of insulation. It has an average thermal conductivity being of about 0.040 W/mK (similar to glass wool and rock wool insulations). An important aspect of loose filled cellulose is very good at fitting around items in walls (like pipes and wiring). Dense-pack cellulose can seal walls from air infiltration whilst providing the density to limit convection, when installed properly.

Sorption properties. Cellulose is a hygroscopic material, and its sorption properties have been described above. The added mineral additives in the insulation material

can increase the water sorption ability. An important parameter for the cellulose insulations is the *moisture buffering value* (the ability of the materials within the room to moderate variations in the RH). This was found to be of about 3.06 [g/m^2 %RH], indicating that this type of insulation can be classified as an 'excellent' moisture buffer (Lopez Hurtado *et al.*, 2016).

The highly hygroscopic nature of cellulose insulation can be detrimental to cellulose-fibre insulations performance. However, it can be beneficial when the regulating humidity conditions inside a building are necessary.

Air infiltration. Openings in a building's envelope can cause air leakage that can have an impact on energy loads in buildings. The cellulose-fibre insulation was found to improve the air tightness with about 36% comparing with the fibreglass (Lopez Hurtado *et al.*, 2016).

Fire properties. The high flammability of cellulosic fibres requires them to be treated before installation in order to achieve acceptable levels of combustion and smouldering resistance. In a typical cellulose-fibre insulation material, borate salts are added to prevent combustion, and boric acid is added to prevent smouldering. Other additives may include aluminium sulphate, aluminium trihydrate, ammonium phosphate and ammonium sulphate (Lopez Hurtado *et al.*, 2016).

Fungal development. Cellulose is a biodegradable material with moisture content and RH having an important role on the fungal growth rate of cellulose insulation. The mould exposure poses a risk to building occupants; therefore, in order to prevent the fungal growth, fungicides need to be added (Lopez Hurtado *et al.*, 2016).

2.6.5 Applications of cellulose as insulation

Cellulose is a renewable and biodegradable polymer, and it has been used for a long time in a wide range of applications: (i) basic materials in papermaking; (ii) main material in textiles made from cotton, linen and other plant fibres and also from viscose or rayon (modified cellulose via the lyocell process); (iii) modified cellulose like microcrystalline cellulose or powdered cellulose can be used as fillers, thickeners and stabilisers in the pharmaceutical and food industry; (iv) energy—the major combustible component of non-food energy crops is cellulose; (v) bioethanol production; (vi) by chemical modification on the cellulose polymers, cellulose derivatives such as cellulose ethers and cellulose ester can be prepared, which have opened up for many novel material and applications for cellulose such as coatings, water-soluble adhesives and binders, films, membranes, new building materials, drilling techniques, pharmaceuticals and food products; (vii) cellulose regeneration process has contributed to novel techniques such as spinning of fibres and the viscose process; and (viii) cellulose nanofibres can be used in different nanocomposite materials with a wide range of applications and (ix) building material.

In the construction sector, cellulose, pulp and paper are mainly used as insulation material, either alone or in combination with resins. As a final product, cellulose insulation is found in two forms: the loose fibres sold in bulk to be manually applied or as a prefabricated panel, in which the cellulose fibres are moulded with a polyester or other similar binder.

(A) (B)

Fig. 2.31 Cellulose insulation types: (A) blown in (http://americanhybridhomes.com/wappingers-cellulose-insulation/) and (B) dense batts (http://www.skylightbrisbane.com.au/gallery/insulation-gallery/, accessed 29.11.2016).

For example, cellulose is seen as an alternative to the more traditional fibreglass-based *blown in* materials (Fig. 2.31A) and is well regarded for its high usage of recyclable materials and relative ease of installation, although it requires specialised blowing in equipment to do so.

It is based on 80% of ground up recycled cellulose or paper, especially newspapers. Most often, fire-retardant materials, such as boric acid or ammonium sulphate (around 15%–20%), are added, when the insulation is used in attics, in wall cavities, in and over the ceiling joist bays or below the rafters with no netting (Service Partners LLC, http://www.service-partners.com/products/cellulose; Adam T Inc., http://www.adamtinc.com/cellulose-insulation-2/). Another method is the so-called dense packing of cellulose and pulp, which is used for floor, wall, ceiling and rafter systems. During the dense-packing installation, netting is first installed on the inner most side of the framing to contain the cellulose within each bay. The cellulose is pneumatically injected one bay at a time through a long hose behind the netting. Cellulose usually contains a lot of small fibres that tend to pack into cracks and crevices of the closed building cavities; therefore, it forms an effective air barrier on its own (http://www.adamtinc.com/cellulose-insulation-2/). Another property of these types of insulation is that they have good acoustical and thermal properties. Cellulose insulation is present also in the form of cellulose batts (Fig. 2.31B) or panels that can be easily installed in sidewalls of the building structures but also in rim joists, attics, floors or other hard to insulate areas (Cellulose Material Solutions, LLC, http://cmsgreen.com/insulation/ecocell-batts).

Synthetic composites have been developed by extruding polypropylene with microcrystalline cellulose obtained by hydrolytic degradation of native cellulose or with regenerated cellulose. These easily accessible composites point towards promising applications.

At the same time, pulp is widely used together with different resins and additives, for the production of medium and high density fiberboards (MDF and HDF).

2.7 Bark and cork

H. Pereira, S. Knapic
University of Lisbon, Lisbon, Portugal

2.7.1 Introduction

Bark covers externally the stems and branches of trees. It has multiple functions: (i) at the physiological level, for example, translocation and storage of organic materials, water storage and photosynthesis in shoots; (ii) as a protective barrier of the tree's inner tissues against biotic attacks, for example, herbivores and pathogens, and external stress conditions, for example, irradiation, desiccation and flooding, snow, extreme temperatures; and (iii) at the ecosystem level, for example, rain water flow and retention, nutrient cycling and fire susceptibility.

The external appearance of barks is very variable and depends on species and tree age, and aspects such as colour, texture and thickness are very heterogeneous. We use barks since ancient times for some of their specific characteristics, namely, of insulation and durability. For instance, in house construction, slabs of birch and poplar were traditionally used for roof and wall cladding; bark was also used for canoes (e.g. birch (*Betula papyrifera*), with bark canoe building still being practised in North America, whilst the now extinct yámanas from Tierra del Fuego built canoes with *Nothofagus betuloides* bark). Commercial production of bark materials for external covering and internal surfacing are available from specialised manufacturers. The barks are peeled off (vertical and horizontal cuts are made through the bark, which is then pulled off gently), cut to planks, steamed, dried and trimmed to the desired dimensions.

Bark is a tree component with a great structural and chemical complexity and diversity. This leads to specific features in the different species and to their potential use for targeted applications such as ropes, textiles, drugs and food, whilst more recently barks are viewed as a potential raw-material for biorefineries, given their characteristics and large availability (Miranda *et al.*, 2012, 2013; Sen *et al.*, 2015). In fact, the accumulation of bark at tree-processing sites and industrial mills represent over 300 million m^3 (Leite and Pereira, 2017).

One of the most interesting bark features is the presence of cork in the outer bark, because cork has a specific set of properties that values it for various applications, of which the world known use as wine bottle stoppers (Fortes *et al.*, 2004; Pereira, 2007). Cork is the basis for an economic relevant production and processing chain and an example of one of the most important non-wood forest products (Pereira and Tomé, 2004).

2.7.2 Formation of bark and cork

Bark is defined as all the tissues to the outside of the wood and vascular cambium, therefore making up the external covering of tree stems and branches (Evert and Eichhorn, 2006). The bark includes different tissues from the inside outwards: (i) the phloem, which is generated by the cambium, and has an inner functional region for conduction and an outer non-functional region; (ii) the periderm that is generated by a cork cambium (called phellogen) forming phelloderm cells to the interior and cork

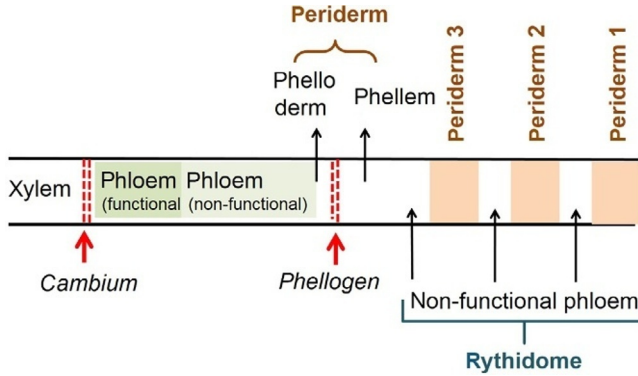


Fig. 2.32 Schematic drawing of a bark (Sen *et al*., 2015).

(also named phellem) to the outside and (iii) the rhytidome that includes various superposed non-functional periderms and phloem tissues between them (Fig. 2.32).

The formation of bark and its thickness increases therefore due to the cell-dividing activity of the two meristems: the cambium that encircles circumferentially the stem and the phellogen that usually is not continuous around the stem; although in some species, for example, the cork oak, it may encircle the stem.

The phloem has different types of cells: sieve elements for water and organic material transfer; axial and radial parenchyma for storage and transport; and fibres and sclereids that provide mechanical support and secretory cells. The proportions of cell types and their arrangement in the phloem differ between species. In contrast, the cork tissue is fairly homogeneous with a regular arrangement of the same type of cells, as detailed further on.

The structure of bark is therefore more complex than that of wood and shows a large diversity between species. Such structural features give bark its macroscopic appearance and underlie some of the specific uses of bark or potential applications, for example, as fibre sources or reinforcement component in composites.

The diversity of barks and their distinction from wood are also present at the chemical level. Bark contains high amounts of inorganic material and of non-structural components that may be solubilised by appropriate solvents, the so-called extractives that usually show a considerable diversity of chemical families and compounds. Many of the traditional uses of barks for medicinal purposes are based on the extractives present, whilst there are proposals on bark valorisation as source of antioxidant and bioactive compounds (Carmo *et al.*, 2016; Ferreira *et al.*, 2017; Miranda *et al.*, 2016). In addition to lignin, cellulose and hemicelluloses, bark has another structural component, suberin, which is specific to the cork tissue in bark.

Cork is one of the most interesting cellular components of bark and largely responsible for its insulation and protective properties. Cork is exploited commercially at large scale from forests of cork oaks (*Quercus suber*) mostly in Portugal and Spain with an annual total production of cork of about 200,000 tons (APCOR, 2015). The cork oak is a very unique species regarding its periderm development, regularity, growth intensity and longevity, as well as regeneration capacity after removal that allows a sustainable production of cork along the tree's life (Pereira, 2007).

Fig. 2.33 From left to right, virgin cork in young cork oak plants, extraction of reproduction cork of a mature cork oak and pile of cork planks.

The cork layer is periodically removed by cutting large planks that are pulled out in late spring or early summer when the phellogen is active and allows an easy separation of the cork (Fig. 2.33). After the cork extraction, a new phellogen is generated at some depth inside the phloem, also with a continuous circumferential development that produces successive layers of cork cells. The first cork extraction takes place at a tree age of 20–25 years, producing the so-called virgin cork that has large fractures (Fig. 2.33), and is industrially triturated for production of cork agglomerates. In the following extractions, the so-called reproduction cork is obtained that has a rather homogeneous thickness and is the raw material for the production of stoppers. The period between cork removals is usually 9 years in the major producing regions, which allows a thickness of the cork plank suitable to produce the cork stoppers (>24 mm).

Cork is used for many products, from sealants to agglomerates and composites, suitable for diverse purposes. The bottle stoppers for the wine industry are the economic driver of the sector but closely associated to the also important insulation and surfacing cork panels for construction and aeronautics, whilst other specialised or niche applications are increasing, for example, pollutants absorbers, clothing and decorative articles (Fortes *et al.*, 2004; Gil, 2009, 2015; Pereira, 2007).

2.7.3 Cork structure and properties

Cork is a cellular material with an interesting set of properties: low density, very little permeability to liquids and gases, chemical and biological inertia, mechanical elasticity, high friction, good insulation and high-damping capacity (Pereira, 2007; Silva *et al.*, 2005). These characteristics are consequence of the material's structure and chemical composition and justify the interest in cork as a raw material (Pereira, 2015).

The cork structure is compact with a very regular arrangement of the individual cells without intercellular spaces. The cells are on average hexagonal prisms that are stacked base-to-base in parallel aligned radial rows. When observed in the transverse section (the plane perpendicular to the plant axis), the structure is a brick-wall type with the cells cut parallel to their prism axis and appearing with a rectangular form;

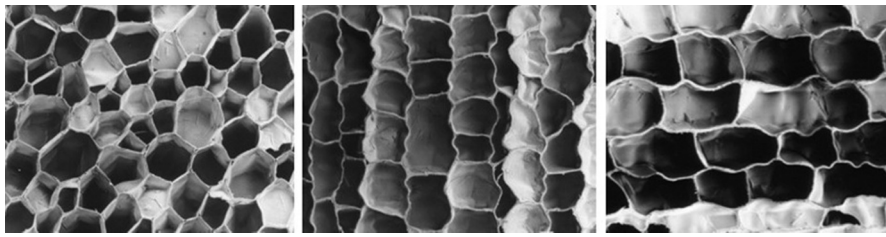


Fig. 2.34 Structure of cork as observed by scanning electron microscopy in the three main sections: (left) tangential section, perpendicular to the tree's radial direction; (middle) transverse section, perpendicular to the tree's axial direction; and (right) radial section, the tree's radial section (Pereira, 2015).

the radial section is very similar. In the tangential section (the plane perpendicular to a stem radius), the cork cells appear polygonal, mostly as hexagons with a honeycomb structure (Fig. 2.34). The cells have on average 40 µm prism height, 20 µm base edge and 1 µm wall thickness, and the cork contains about 4×10^7–7×10^7 cells per cubic metre corresponding to a solid fraction under 20% of the total volume (Pereira, 2007). The cell walls often show undulations, especially the lateral prism faces that in most cases have 2–3 undulations per face but that can increase to intense corrugation or to irregular patterns if subjected to stress (Pereira, 2007). Cork is anisotropic due to the cell orientation, but the shape anisotropy ratios are small, and the properties measured in the three main directions differ much less than those of wood.

Chemically, cork has on average 16% extractives, 43% suberin, 22% lignin and 19% cellulose and hemicelluloses (Pereira, 2013). The content of suberin is the most important chemical attribute of cork since it is directly related to most of its typical properties; lignin is the second most important structural component and also determines the behaviour of the material (Pereira, 2015). Contrarily to what happens in wood, cellulose has a lesser role in the construction of the cork cell wall and for the material's properties (Pereira, 2013).

Cork is a light material with density values ranging from below 120 to over 200 kg/m^3. It absorbs water very slowly and floats on water with large buoyancy. The diffusion of water in cork is considerably slow (Rosa and Fortes, 1993), as it is also the permeability to liquid water and vapour, and to non-condensable gases (Brazinha *et al.*, 2013; Faria *et al.*, 2011; Fonseca *et al.*, 2013; Lequin *et al.*, 2012). The surface of cork is hydrophobic with a low wettability regarding polar liquids (e.g. water) and high affinity for non-polar liquids (e.g. non-polar resins) (Abenojar *et al.*, 2014). Cork has very low heat transfer properties due to both its large air content and small cell size (Pereira, 2007; Silva *et al.*, 2005). Similarly, sound transmission is very low (Knapic *et al.*, 2016).

The mechanical properties of cork have been studied in detail especially regarding its behaviour under compression (Gibson *et al.*, 1981; Rosa and Fortes, 1988; Anjos *et al.*, 2008). Cork allows large deformations under compression without fracture, with substantial dimensional recovery when stress is relieved. A typical stress-strain curve shows an elastic region up to about 5% strain, followed by a broad plateau where the collapse of cells by cell wall buckling allows strong dimensional reductions for small

stress increases. Young's modulus averages are 10.4 and 9.2 MPa for the radial and non-radial directions, respectively (Oliveira *et al.*, 2014). The variation in compression in different directions is not very large, although resistance is lower in the non-radial directions when compared with the radial direction (Anjos *et al.*, 2014). Cork does not fracture under compression; instead, it undergoes a process of densification for high stresses over 60% strain. Fig. 2.35 shows the variation of the cellular structure of cork under compression where the capacity of cell wall folding without fracture is evident. When cork is compressed in one direction, the dimensions in the directions perpendicular to the stress do not vary (or only very little), due to its small Poisson's ratios (Fortes and Nogueira, 1989). The recovery of the original dimensions after stress removal is rapid and is associated with the unfolding of buckled cell walls with a small permanent deformation after 50% strain (from −3% to −9%) (Anjos *et al.*, 2014).

In tension, the stress and strain curves of cork show a linear elastic region until ~2% strain (stress at 0.4 MPa), and fracture at an average stress of 0.6 MPa (strain of 5%) (Anjos *et al.*, 2010). In bending, cork fractures at the side under tension when the tensile strength is overcome (Anjos *et al.*, 2011).

The classification of natural cork regarding reaction to fire is not well established but expanded corkboards (insulation corkboards) and cork-polymer composites qualify as a class E (EN 13501-1 (CEN, 2007b)). When subjected to heating, cork has no emissions of furfural or acetic acid (Salthamer and Fuhrmann, 2000). In fact, the chemical composition gives cork a high thermal stability when compared with that of synthetic polymers that degrade and melt at comparatively low temperatures. The thermal stability of suberin and the low hemicelluloses content of cork give cork a better performance at elevated temperatures (Sen *et al.*, 2012, 2014), and even at very high temperatures over 2000°C, the cork structural backbone is maintained (Reculusa *et al.*, 2006). This allows cork to be used as an insulation layer in case of fire.

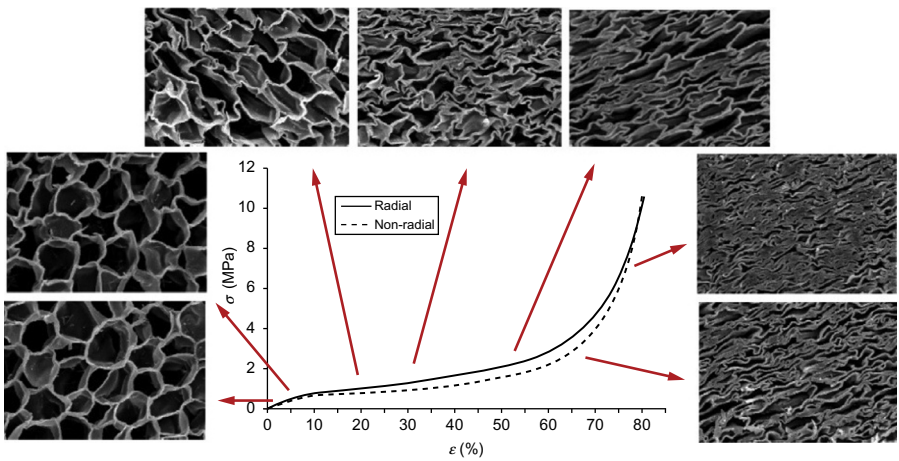


Fig. 2.35 Compression of cork in radial and non-radial directions and variation of the cellular structure with increasing stains as exemplified by scanning electron micrographs of cork tangential section at various axial compression strains (Pereira, 2015).

2.7.4 Cork in construction

The properties of insulation, wear resistance and durability make cork suitable for use in buildings, whilst its favourable ecological footprint meets green building demands. The different cork-based materials that may be used in building can be grouped as (Knapic *et al.*, 2016):

(i) unprocessed cork planks obtained by removal from the tree stem
(ii) granulated cork
(iii) cork agglomerates as composites of cork granules and resin
(iv) expanded cork agglomerates without resin
(v) rubber-cork composites

Most of the applications of cork in construction are based on the different types of cork agglomerates and composites, whilst the use of raw cork (cork planks or slabs) or of natural cork components (intermediate or residual products in the industrial processing) is not very widespread and in general restricted to special designs. For instance, Fig. 2.36 shows an external wall cladding using slabs of virgin and of reproduction cork and an internal partitioning solution using residues from the production

Fig. 2.36 Above row, external cladding with slabs of virgin and reproduction cork in the Observatório do Sobreiro e da Cortiça, Coruche, Portugal (architect Manuel Couceiro), interior portioning in the same building using by-products from the production of stoppers. Bottom row, Portuguese pavilion with external cladding with expanded cork agglomerate boards (architect Carlos Couto) in the Shanghai 2010 World Exposition (China) and external entrance wall of the Museo del Suro, in Palafrugell (Spain) using recycled cork stoppers.

of cork discs for sparkling wine stoppers. The media coverage of some cork applications as exterior cladding of buildings increased public awareness on cork, for example, the Portuguese pavilions in the last two World Expositions of Hanover 2000 and Shanghai 2010 (Fig. 2.36).

Most of the uses of cork products in construction are related to thermal insulation and energy absorption properties in combination with physical, chemical and biological stabilities. The antivibrational, thermal and acoustic absorbing properties underlie several applications like flooring, wall and ceiling tiles or underlay, gaskets, expansion joints, and external cladding, as well as in concrete and road pavement. Examples of cork products used in construction and the properties valued in each case are shown in Table 2.7 (Knapic *et al.*, 2016).

Cork agglomerates are produced using the large amount of residual by-products from the manufacture of cork stoppers and discs and also from the refuse raw cork planks and other types of cork raw materials such as virgin cork (Pereira, 2007). Cork granules of different dimensions and density are produced by trituration and subsequent fractionation into different granulates, for example,

Table 2.7 Cork products used in different applications in construction and their underlying properties (Knapic *et al.*, 2016)

Uses	Products	Examples	Required properties
Coverings (floors, walls and ceilings)	Agglomerated cork composites Expanded cork agglomerates Rubber-cork composites	Cork tiles for flooring Underlay for ceilings Underlay for flooring	Wear resistance Resilience Shock absorption
Thermal and acoustic insulation	Agglomerated cork composites Expanded cork agglomerates Granulated cork	Cork epoxy agglomerates Interior wall and roof panels Filling between double walls and floors	Low thermal conductivity No moisture absorption Adequate mechanical resistance Fire resistance Durability Low density
Vibration insulation	Agglomerated cork composites Expanded agglomerated cork Rubber cork	Sandwich-type structures Expanded corkboards with high density Structural joints	Vibration shock absorption
Expansion joints	Agglomerated cork composites Rubber cork	Expanded corkboards	High compressibility and recovery

1–10, 2–5, 1–2, 0.5–1 and 0.2–0.5 mm as specified by the targeted product. The cork granules may be directed to three processing lines: (i) the production of cork composites with a resin binding the cork granules, (ii) the production of expanded cork agglomerates under superheated steaming and without external binding agent and (iii) the copolymerisation with rubber to make rubber-cork composites (Knapic *et al.*, 2016).

The agglomerated cork composites are used mostly for surface coverings such as wall panels and flooring applications and a core material in sandwich-type structures. Their use has increased in recent years, and several public buildings selected cork agglomerates for the flooring, for example, the Sagrada Familia cathedral in Barcelona.

The expanded cork agglomerates are used mostly for thermal and acoustic insulation and for vibration absorption in roofs, walls, floors and ceilings, as well as for sound absorption in noisy environments or to insulate from external sounds and reduce reverberation (Gil, 2007). Interior partitioning may use sandwich panels of wood veneer and a core of expanded cork agglomerate (Lakreb *et al.*, 2015).

Granules of expanded cork (from 0.25 to 22.4 mm) can be used for thermal insulation, filling empty spaces between double walls, floors or as a roof ceiling application. Such cork granulates also have high sound absorption performance (Maderuelo-Sanz *et al.*, 2014a) and may be mixed with polyurethane and epoxy resins (Maderuelo-Sanz *et al.*, 2014b).

The cork-rubber composites are used for gaskets and sealing systems in the automobile industry, vibration and acoustic insulation for industrial machinery, civil engineering and railways, gaskets for electrical transformers, heaters and gas metres or heavy-duty flooring and footwear (Pereira, 2007; Gil, 2007).

Other cork products may also be used such as cork-assembled materials and cork composites with other materials that take advantage of the insulation properties and the low density of cork, that is, cork gypsum (Hernandéz-Olivares *et al.*, 1999; Panesar and Shindman, 2012), lightened plaster (Rio Merino *et al.*, 2005), lightweight polymer mortar (Nóvoa *et al.*, 2004) and concrete (Aziz *et al.*, 1979; Branco *et al.*, 2008; Pereira, 2007).

Incorporation of cork granules in cemented mortars brings lower relative density (1900–2300 kg/m^3) when compared with concrete (around 2400 kg/m^3) and a reduction on the production costs. (Carvalho *et al.*, 2013), Cork may be used to produce lightweight concrete (Aziz *et al.*, 1979) and to improve concrete thermal resistance although with some reduction of mechanical properties (Branco *et al.*, 2007, 2008; Silva *et al.*, 2005). The presence of cork improves the thermal behaviour of concrete block walls and makes them lighter and easier to handle (Castro *et al.*, 2010).

The use of cork products as building materials can be a valuable contribution for lowering energy intensity and environmental impacts of buildings (Gil, 2011). For instance, EPS or polyurethane is responsible for the emission of, on average, 7 kg CO_2-eq/kg with high consumptions of gas and petroleum, whilst insulation materials of natural origin, such as cork, emit only 0.8 kg CO_2-eq/kg (Zabalza Bribián *et al.*, 2011). In parallel with its advantageous properties as a material, cork is associated to sustainable and environmentally rich production systems since the cork oak stands

play an important role in ecological protection, water retention and soil conservation and for fauna and flora biodiversity (WWF, 2006; Pereira, 2007).

Cork is a green product, and the expanded insulation cork is amongst the 'top 10 green building products' list (Building Green, Inc., http://www2.buildinggreen.com/buildinggreens-top-10-products-2013). The recycling of cork products extends the lifetime of products, thus increasing the emissions delay of the carbon fixed by the cork oak tree and incorporated in cork, thereby allowing a more efficient building reuse and construction waste management.

References

Abenojar, J., Barbosa, A.Q., Ballesteros, Y., del Real, J.C., da Silva, L.F.M., Martínez, M.A., 2014. Effect of surface treatments on natural cork: surface energy, adhesion, and acoustic insulation. Wood Sci. Technol. 48, 207–224.

Agarwal, U.P., Atall, R.H., 2010. Vibrational spectroscopy. In: Heitner, C., Dimmel, D., Schmidt, J.A. (Eds.), Lignin and Lignans: Advances in Chemistry. CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 103–136.

Alistair, M.S., 1995. Food Polysaccharides and Their Applications. Marcel Dekker Inc, New York.

Anjos, O., Pereira, H., Rosa, M.E., 2008. Effect of quality, porosity and density on the compression properties of cork. Holz Roh Werkst. 66, 295–301.

Anjos, O., Pereira, H., Rosa, M.E., 2010. Tensile properties of cork in the tangential direction: variation with quality, porosity, density and radial position in the cork plank. Mater. Des. 31, 2085–2090.

Anjos, O., Pereira, H., Rosa, M.E., 2011. Characterization of radial bending properties of cork. Eur. J. Wood Wood Prod. 69, 557–563.

Anjos, O., Rodrigues, C., Morais, J., Pereira, H., 2014. Effect of density on the compression behaviour of cork. Mater. Des. 53, 1089–1096.

APCOR, 2015. Cork Information Bureau 2014. Construction and decoration materials. http://www.apcor.pt/userfiles/File/CIB/Construction_and_Decoration_Materials_EN.pdf.

Asif, M., 2009. Sustainability of timber, wood and bamboo in construction. In: Khatib (Ed.), Sustainability of Construction Materials. Woodhead Publishing, Cambridge.

Aziz, M.A., Murphy, C.K., Ramaswamy, S.D., 1979. Lightweight concrete using cork granules. Int. J. Cem. Compos. Lightweight Concr. 1 (1), 29–33.

Baird, P.K., Schwarzt, S.L., 1956. Hardboard: processes, properties and potentials. Report D1928 United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Bajpai, P., 2005. Environmentally Benign Approaches for Pulp Bleaching. Elsevier Science BV, Amsterdam.

Bajpai, P., 2012. Biotechnology for Pulp and Paper Processing. Springer, New York, NY.

Bajracharya, R.M., Manalo, A.C., Karunasena, W., Lau, K., 2014. An overview of mechanical properties and durability of glass-fibre reinforced recycled mixed plastic waste composites. Mater. Des. 62, 98–112.

Baker, C.F., 2005. Advances in the practicalities of refining. In: Scientific and Technical Advances in Refining and Mechanical Pulping, 8th Pira International Refining Conference, Pira International, Barcelona, Spain.

Ballerini, A., Despres, A., Pizzi, A., 2005. Non-toxic, zero emission tannin-glyoxal adhesives for wood panels. Holz Roh Werkst. 63 (6), 477–478.

Ballerini, A.A., Bustos, X.A., Nunez, M.A., Wechsler, A., 2008. Innovation in window and door profile designs using a wood-plastic composite. In: Proc. of the International Convention Society of Wood Science and Technology, Conception, Chile.

Bartlett, C., 2015. MDF: closed loop recycling—enhancing supply chain value. In: Proceedings of the International Panel Products Symposium, 7th–8th October 2015, Llandudno.

Berger, M.J., Stark, N.M., 1997. Effect of species and particle size on properties of wood-flour reinforced polypropylene composites. In: Proceeding of Functional Fillers for Thermoplastic and Thermosets, December 8–10, Le Meridien at Coronado, San Diego, California, USA.

Bernheimer, A. (Ed.), 2014. Timber in the City—Design and Construction in Mass Timber. Oro Editions, New York, NY.

Berthold, J., Rinaudo, M., Salmen, L., 1996. Association of water to polar groups—estimations by an adsorption model for lignocellulosic materials. Colloids Surf. A 112, 117–129.

Boonstra, M.J., Tjeerdsma, B., 2006. Chemical analysis of heat treated softwoods. Holz Roh Werkst. 64, 204–211.

Boonstra, M.J., Van Acker, J., Tjeerdsma, B.F., Kegel, E.V., 2007. Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents. Ann. For. Sci. 64, 679–690.

Branco, F.G., Tadeq, A., Reis, C., 2007. Can cork be used as a concrete aggregate? Int. J. Hous. Sci. 31 (1), 1–11.

Branco, F.G., Reis, M.L.B.C., Tadeu, A., 2008. Experimental evaluation of the durability of cork concrete. Int. J. Hous. Sci. 32, 149–162.

Brazinha, C., Fonseca, A.P., Pereira, H., Teodoro, O.M.N.D., Crespo, J.G., 2013. Gas transport through cork: modelling gas permeation based on the morphology of a natural polymer material. J. Membr. Sci. 428, 52–62.

Brege, S., Stehn, L., Nord, T., 2014. Business models in industrialized building of multi-storey houses. Constr. Manag. Econ. 32 (1–2), 208–226.

Bucur, V., 2006. Acoustics of Wood, second ed. Springer-Verlag, Berlin, Heidelberg.

Bugnicourt, E., Cinelli, P., Lazzeri, A., Alvarez, V., 2014. Polyhydroxyalkanoate (PHA): review of synthesis, characteristics, processing and potential applications in packaging. Express Polym. Lett. 8 (11), 791–808.

Burr, T. 2009. Building Schools for the Future. National Audit Office. https://www.nao.org.uk/report/the-building-schools-for-the-future-programme-renewing-the-secondary-school-estate/.

Cai, Z., Ross, R.J., 2010, Mechanical properties of wood-based composite materials. In: Wood Handbook: Wood as an Engineering Material. General technical report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Candan, Z., Büyüksarı, U., Korkut, S., Unsal, O., Çakıcıer, N., 2012. Wettability and surface roughness of thermally modified plywood panels. Ind. Crop. Prod. 36, 434–436.

Carmo, J.F., Miranda, I., Quilhó, T., Sousa, V.B., Cardoso, S., Carvalho, A.M., Carmo, F.H.D.J., Latorraca, J.V.F., Pereira, H., 2016. *Copaifera langsdorffii* bark as a source of chemicals: structural and chemical characterization. J. Wood Chem. Technol. 36, 305–317.

Carus, M., Eder, A., Dammer, L., Korte, H., Scholz, L., Essel, R., Breitmayer, E., Barth, M., 2015. Wood Plastic Composites (WPC) and Natural Fibre Composites (NFC): European and Global Markets 2012 and Future Trends in Automotive and Construction. Nova-Institut GmbH; Germany.

Carvajal, O., Valdés, J.L., Puig, J., 1996. Bagasse particleboards for building purpose. Holz Roh Werkst. 54, 61–63.

Carvalho, R., Teixeira-Dias, F., Varum, H., 2013. Cyclic behaviour of a lightweight mortar with cork granulate composite. Compos. Struct. 95, 748–755.
Castro, O., Silva, J.M., Tessaleno, D., Silva, A., Gil, L., 2010. Cork agglomerates as an ideal core material in lightweight structures. Mater. Des. 31, 425–432.
CEN, 1993. EN 314-2:1993. Plywood: Bonding Quality. Requirements. European Committee for Standardization, Brussels, Belgium.
CEN, 1994. EN 460:1994. Durability of Wood and Wood-Based Products. Natural Durability of Solid Wood. Guide to the Durability Requirements for Wood to be Used in Hazard Classes. European Committee for Standardization, Brussels, Belgium.
CEN, 1995. EN 1995-1:1995. Eurocode 5: Design of Timber Structures. European Committee for Standardization, Brussels, Belgium.
CEN, 2003a. EN 1088-1:2003. Marine Plywood: Requirements. European Committee for Standardization, Brussels, Belgium.
CEN, 2003b. BS 1088-2:2003. Marine Plywood. Determination of Bonding Quality Using the Knife Test. European Committee for Standardization, Brussels, Belgium.
CEN, 2003c. EN 622-1:2003. Fibreboards. Specifications. General Requirements. European Committee for Standardization, Brussels, Belgium.
CEN, 2004. EN 622-2:2004. Fibreboards. Specifications. Part 2: Requirements for Hardboards. European Committee for Standardization, Brussels, Belgium.
CEN, 2006. EN 300:2006. Oriented Strand Boards (OSB). Definitions, Classification and Specifications. European Committee for Standardization, Brussels, Belgium.
CEN, 2007a. EN 351-1:2007. Durability of Wood and Wood-Based Products Preservative-Treated Solid Wood. Part 1: Classification of Preservative Penetration and Retention. European Committee for Standardization, Brussels, Belgium.
CEN, 2007b. EN 13501-1: 2007. Fire classification of construction products and building elements. Classification using test data from reaction to fire tests. European Committee for Standardization, Brussels, Belgium.
CEN, 2009a. EN 622-4:2009. Fibreboards. Specifications. Part 4: Requirements for Softboards. European Committee for Standardization, Brussels, Belgium.
CEN, 2009b. EN 622-5:2009. Fibreboards. Specifications. Part 5: Requirements for Dry Process Boards (MDF). European Committee for Standardization, Brussels, Belgium.
CEN, 2010. EN 312:2010. Particleboards: Specifications. European Committee for Standardization, Brussels, Belgium.
CEN, 2013. EN 335:2013. Durability of Wood and Wood-Based Products. Definitions of Use Classes. General. European Committee for Standardization, Brussels, Belgium.
CEN, 2015. EN 636:2012+A1:2015. Plywood. Specifications. European Committee for Standardization, Brussels, Belgium.
CEN, 2016. EN 350:2016. Durability of wood and wood-based products – Testing and classification of the durability to biological agents of wood and wood-based materials. European Committee for Standardization, Brussels, Belgium.
Chaharmahali, M., Mirbagheri, J., Tajvidi, M., Najafi, S.K., Mirbagheri, Y., 2010. Mechanical and physical properties of wood plastic composite panels. J. Reinf. Plast. Compos. 29 (2), 310–319.
Chen, H., 2014. Chemical composition and structure of natural lignocellulose. In: Biotechnology of Lignocellulose: Theory and Practice. Chemical Industry Press, Beijing, pp. 25–71.
Chen, Y.P., Li, H., Li, D.Q., Zhang, T., 2012. Effects on stress wave speed inside wood members in historical buildings. China Wood Ind. 26 (2), 37–40.
Cheng, W., Han, G., Fang, D., 2013. Oriented structural boards from split wheat straw: effects of straw length, panel density, and resin content. Bioresources 8 (3), 4497–4504.
Clemons, C., 2002. Wood-plastic composites in the United States: the interfacing of two industries. For. Prod. J. 52, 10–18.

Crawford, T.C., Crawford, S.A., 1980. Synthesis of L-ascorbic acid. Adv. Carbohydr. Chem. Biochem. 37, 79–155.

Curling, S., 1998. The decay of wood based board materials by basidiomycete fungi (PhD thesis). University of London.

Curling, S., Murphy, R., 1999. The effect of artificial ageing on the durability of wood based board materials against basidiomycete decay fungi. Wood Sci. Technol. 33 (4), 245–257.

Curling, S.F., Stefanowski, B.K., Laflin, N., Davies, G., Ormondroyd, G.A., 2016. The effect on panel properties of incorporation of reject paper fibre into MDF panels. Int. Wood Prod. J. 7 (3), 165–170.

Czajkowski, Ł., Olek, W., Weres, J., Guzenda, R., 2016. Thermal properties of wood-based panels: specific heat determination. Wood Sci. Technol. 50, 537–545.

Davis, E., Shale, S.K., Goodell, B., 2003. The incorporation of paper deinking sludge into fibreboard. For. Prod. J. 53 (11–12), 46–54.

Dence, C.W., Lin, S.Y., 1992. Methods in Lignin Chemistry. Springer Verlag, Berlin; Heidelberg, pp. 3–6.

Despres, A., Pizzi, A., Vu, C., Delmotte, L., 2010. Colourless formaldehyde-free urea resin adhesives for wood panels. Eur. J. Wood Wood Prod. 68, 13–20.

Ding, W.D., Kouba, A., Chaala, A., Belem, T., Krause, C., 2008. Relationship between wood porosity, wood density and methyl methacrylate impregnation rate. Wood Mater. Sci. Eng. 3 (1–2), 62–70.

Eder, A., Carus, M., 2013. Global trends in composites (WPC). Bioplastics Mag. 8, 16–17.

Engelund, E.T., Thygesen, L.G., Svensson, S., Hill, C.A.S., 2013. A critical discussion of the physics of wood–water interactions. Wood Sci. Technol. 47, 141–161.

English, B., Stark, N., Clamons, C., 1996. Wood and mineral fillers for injection molding grade polypropylene, Madison, USA.

Ermeydan, M.A., Cabane, E., Hass, P., Koetzd, J., Burgert, I., 2014. Fully biodegradable modification of wood for improvement of dimensional stability and water absorption properties by poly(ε-caprolactone) grafting into the cell walls. Green Chem. 16, 3313–3321.

Esteves, B.M., Pereira, H.M., 2009. Wood modification by heat treatment: a review. Bioresources 4, 370–404.

Evert, R.F., Eichhorn, S.E., 2006. Esau's Plant Anatomy, Meristems, Cells, and Tissues of the Plant Body: Their Structure, Function, and Development, third ed. John Wiley & Sons, New York, NY.

Fardim, P., Liebert, T., Heinze, T., 2012. Pulp fibers for papermaking and cellulose dissolution. In: Navard, P. (Ed.), The European Polysaccharide Network of Excellence (EPNOE). Springer, New York, NY, pp. 253–282.

Faria, D.P., Fonseca, A.L., Pereira, H., Teodoro, O.M.N.D., 2011. Permeability of cork to gases. J. Agric. Food Chem. 59, 3590–3597.

Fengel, D., Wegener, G., 1989. Wood: Chemistry, Ultrastructure and Reactions. Walter de Guiter, Berlin.

Fernando, D., Frangi, A., Kobel, P., 2016. Behaviour of basalt fibre reinforced polymer strengthened timber laminates under tensile loading. Eng. Struct. 117, 437–456.

Ferreira, J.P.A., Quilhó, T., Pereira, H., 2017. Characterization of *Betula pendula* outer bark regarding cork and phloem components at chemical and structural levels in view of biorefinery integration. J. Wood Chem. Technol. 37 (1), 10–25.

Fonseca, A.L., Brazinha, C., Pereira, H., Crespo, J.G., Teodoro, O.M.N.D., 2013. Permeability of cork for water and ethanol. J. Agric. Food Chem. 61, 9672–9679.

Fortes, M.A., Nogueira, M.T., 1989. The Poisson effect in cork. Mater. Sci. Eng. A 122, 227–232.

Fortes, M.A., Rosa, M.E., Pereira, H., 2004. A Cortiça. IST Press, Lisboa.

Freedonia/Fordaq, http://www.fordaq.com/fordaq/news/US_wood-plasticcomposite_plastic_lumber_47517.html. (08.06.2016).

Gagnon, S., Pirvu, C. (Eds.), 2011. CLT Handbook: Cross Laminated Timber. FP Innovations, Quebec, Vancouver.
Geng, X., Zhang, S.Y., Deng, J., 2007. Characteristics of paper mill sludge and its utilization for the manufacture of medium density fiberboard. J. Wood Fiber Sci. 39 (2), 345–351.
Gibson, L.J., Easterlinge, K.E., Ashby, M.F., 1981. The structure and mechanics of cork. Proc. R. Soc. Lond. A 377 (1769), 99–117.
Gil, L., 2007. Cork as a Building Material. Technical Manual. APCOR, Santa Maria de Lamas.
Gil, L., 2009. Cork composites: a review. Materials 2, 776–789.
Gil, L., 2011. Environmental, sustainability and ecological aspects of cork products for building. Ciência Tecnol. Mat. 23, 87–90.
Gil, L., 2015. Cork: sustainability and new applications. Front. Mater. 1, 38.
Glass, S.V., Zelinka, S.L., 2010. Moisture relations and physical properties of wood. In: Wood Handbook-Wood as an Engineering Material. General technical report FPL-GTR-190. Forest Products Laboratory; Madison, WI, pp. 4.1–4.19.
Green, M., 2012. Tall Wood. Canadian Wood Council (CWC), Forestry Innovation Investment (FII).
Grigoriou, A.H., 2003. Waste paper–wood composites bonded with isocyanate. Wood Sci. Technol. 37 (1), 79–90.
Han, J.S., Rowell, J.S., 1996. Chemical composition of fibers. In: Rowell, R.M., Young, R.A., Rowell, J. (Eds.), Paper and Composites From Agro-Based Resources. CRC Press, London, pp. 83–130.
Heinze, T., 2016. Cellulose chemistry and properties: fibers, nanocelluloses and advanced materials, cellulose: structure and properties. Adv. Polym. Sci. 271, 1–52.
Hernandéz-Olivares, F., Bollati, M.R., del Rio, M., Parga-Landa, B., 1999. Development of cork gypsum composites for building applications. Constr. Build. Mater. 13, 179–186.
Hill, C.A.S., 2006. Wood Modification: Chemical, Thermal and Other Processes. John Wiley & Sons, Chichester; Hoboken, NJ.
Hillis, W.E., Rozsa, A.N., 1985. High temperature and chemical effects on wood stability—part 2. The effect of heat on the softening of radiata pine. Wood Sci. Technol. 19, 57–66.
Hodgson, K.T., 1997. Overview of sizing. In: Tappi Sizing Short CourseS1. TAPPI, Nashville.
Hohne, P., Tauer, K., 2016. Studies on swelling of wood with water and ionic liquids. Wood Sci. Technol. 50, 245–258.
Huang, C.-L., Lindstrom, H., Nakada, R., Ralston, J., 2003. Cell wall structure and wood properties determined by acoustics—a selective review. Holz Roh Werkst. 61, 321–335.
Hughes, M., 2015. Plywood and other veneer-based products. In: Ansell, M.P. (Ed.), Wood Composites. Woodhead Publishing, Cambridge.
Hull, D., Clyne, T.W., 1996. An Introduction to Composite Materials, second ed. Cambridge University Press, Cambridge.
Hurmekoski, E., Jonsson, R., Nord, T., 2015. Context, drivers, and future potential for wood-frame multi-story construction in Europe. Technol. Forecast. Soc. Chang. 99, 181–196.
Isik, M., Sardon, H., Mecerreyes, D., 2014. Ionic liquids and cellulose: dissolution, chemical modification and preparation of new cellulosic materials. Int. J. Mol. Sci. 15, 11922–11940.
ISO, 2015. ISO 16616:2015. Test methods for natural fibre—reinforced plastic composite (NFC) deck boards. International Organization for Standardization, Geneva, Switzerland.
Ivanović-Šekularac, J., Čikić-Tovarović, J., Šekularac, N., 2016. Application of wood as an element of façade cladding in construction and reconstruction of architectural objects to improve their energy efficiency. Energ. Buildings 115, 85–93.
Joly, C., Gauthier, R., Escoubes, M., 1996. Partial masking of cellulosic fiber hydrophilicity for composite applications—water sorption by chemically modified fibers. J. Appl. Polym. Sci. 61, 57–69.

Kalia, S., Dufresne, A., Cherian, B.M., Kaith, B.S., Avérous, L., Njuguna, J., Nassiopoulos, E., 2011. Cellulose-based bio- and nanocomposites: a review. Int. J. Polym. Sci. http://dx.doi.org/10.1155/2011/837875. Article ID 837875, p. 35.

Kallakas, H., Poltimäe, T., Süld, T.-M., Kers, J., Krumme, A., 2015. The influence of accelerated weathering on the mechanical and physical properties of wood-plastic composites. Proc. Est. Acad. Sci. 64 (1S), 94–104.

Kapfinger, O., Wieder, U. (Eds.), 2007. Riess Wood3—Modulare Holz. Springer Verlag, Vienna; New York, NY.

Kaufmann, H., Nerdinger, W. (Eds.), 2011. Building With Timber—Paths Into the Future. Prestel Verlag, London; Munich; New York, NY.

Khelifa, M., Auchet, S., Méausoone, P.-J., Celzard, A., 2015. Finite element analysis of flexural strengthening of timber beams with carbon fibre-reinforced polymers. Eng. Struct. 101, 364–375.

Kielmann, B.C., Mai, C., 2016. Natural weathering performance and the effect of light stabilizers in water-based coating formulations on resin-modified and dye-stained beech-wood. J. Coat. Technol. Res. 13 (6), 1065–1074.

Kim, J.K., Pal, K., 2011. Recent Advances in the Processing of Wood-Plastic Composites. Springer, Berlin; Heidelberg.

Klemm, D., Heublein, B., Fink, H.-P., Bohn, A., 2005. Cellulose: fascinating biopolymer and sustainable raw material. Angew. Chem. Int. Ed. 44, 3358–3393.

Klyosov, A.A., 2007. Wood-plastic composites. John Wiley & Sons, USA.

Knapic, S., Oliveira, V., Saporiti Machado, J., Pereira, H., 2016. Cork as a building material: a review. Eur. J. Wood Wood Prod. 74, 775–791.

Kollman, F.F.P., Kuenzi, E.W., Stamm, A.J., 1975. Principles of Wood Science and Technology II; Wood Based Materials. Springer, New York, NY.

Kose, C., Terzi, E., Büyüksarı, Ü., Avcı, E., Ayrılmış, N., Kartal, S.N., Imamura, Y., 2011. Particleboard and MDF panels made form a mixture of wood and pinecones: resistance to decay fungi and termites under laboratory conditions. BioResources 6, 2045–2054.

Kretschmann, D.E., 2010. Mechanical properties of wood. In: Wood Handbook—Wood as an Engineering Material. General technical report FPL-GTR-190. Forest Products Laboratory; Madison, WI, pp. 5.1–5.44.

Kutnik, M., Suttie, E., Brischke, C., 2014. European standards on durability and performance of wood and wood based products—trends and challenges. Wood Mater. Sci. Eng. 9 (3), 122–133.

La Mantia, F., Morreale, M., 2011. Green composites: a brief review. Compos. A: Appl. Sci. Manuf. 42, 579–588.

Lakreb, N., Bezzazia, B., Pereira, H., 2015. Mechanical strength properties of innovative sandwich panels with expanded cork agglomerates. Eur. J. Wood Wood Prod. 73, 465–473.

Leite, C., Pereira, N., 2017. Cork containing barks—a review. Front. Mater. 3, Art.63, 1–19.

Lequin, S., Chassagne, D., Karbowiak, T., Simon, J.M., Paulin, C., Bellat, J.P., 2012. Diffusion of oxygen in cork. J. Agric. Food Chem. 60 (13), 3348–3356.

Li, B., He, J., 2004. Investigation oft he mechanical property, flame retardancy and thermal degradation of LLDPE-wood fiber composites. Polym. Degrad. Stab. 83, 241–246.

Lopez Hurtado, P., Rouilly, A., Vandenbossche, V., Raynaud, C., 2016. A review on the properties of cellulose fibre insulation. Build. Environ. 96, 170–177.

Maderuelo-Sanz, R., Morillas, J.M.B., Escobar, V.G., 2014a. Acoustical performance of loose cork granules. Eur. J. Wood Wood Prod. 72, 321–330.

Maderuelo-Sanz, R., Morillas, J.M.B., Escobar, V.G., 2014b. The performance of resilient layers made from cork granulates mixed with resins for impact noise reduction. Eur. J. Wood Wood Prod. 72, 833–835.

Mayo, J., 2015. Solid Wood—Case Studies in Mass Timber Architecture, Technology and Design. Routledge, London; New York, NY.
Migneault, S., Koubaa, A., Nadji, H., Riedel, B., Zhang, S.Y., Deng, J., 2010. Medium-density fiberboard produced using pulp and paper sludge from different pulping processes. Wood Fiber Sci. 42 (3), 292–303.
Miranda, I., Gominho, J., Mirra, I., Pereira, H., 2012. Chemical characterization of barks from *Picea abies* and *Pinus sylvestris* after fractioning into different particle sizes. Ind. Crop. Prod. 36, 395–400.
Miranda, I., Gominho, J., Mirra, I., Pereira, H., 2013. Fractioning and chemical characterization of barks of *Betula pendula* and *Eucalyptus globulus*. Ind. Crop. Prod. 41, 299–305.
Miranda, I., Lima, L., Quilhó, T., Knapic, S., Pereira, H., 2016. The bark of *Eucalyptus sideroxylon* as a source of phenolic extracts with anti-oxidant properties. Ind. Crop. Prod. 82, 81–87.
Mohebby, B., Gorbani-Kokandeh, M., Soltani, M., 2009. Springback in acetylated wood based composites. Constr. Build. Mater. 23, 3103–3106.
Monteiro de Barros Filho, R., Mendes, L.M., Novack, K.M., Aprelini, L.O., Botaro, R.V., 2011. Hybrid chipboard panels based on sugarcane bagasse, urea formaldehyde and melamine formaldehyde resin. Ind. Crop. Prod. 33 (2), 369–373.
Moon, R.J., Martini, A., Nairn, J., Simonsen, J., Youngblood, J., 2011. Cellulose nanomaterials review: structure, properties and nanocomposites. Chem. Soc. Rev. 40, 3941–3994.
Moubarik, A., Charrier, B., Allal, A., Charrier, F., Pizzi, A., 2010. Development and optimization of a new formaldehyde-free cornstarch and tannin wood adhesive. Eur. J. Wood Wood Prod. 68, 167–177.
Mullens, M.A., Arif, M., 2006. Structural insulated panels: impact on the residential construction process. J. Constr. Eng. Manag. 132, 786–794.
Najafi, K.S., 2013. Use of recycled plastics in wood plastic composites—a review. Waste Manag. 33, 1898–1905.
Nakamura, K., Hatakeyama, T., Hatakeyama, H., 1981. Studies on bound water of cellulose by differential scanning calorimetry. Text. Res. J. 51, 607–613.
Naumann, A., Seefeldt, H., Stephan, I., Braun, U., Noll, M., 2012. Material resistance of flame retarded wood-plastic composites against fire and fungal decay. Polym. Degrad. Stab. 97, 1189–1196.
Nilsson, T., Rowell, R., 2012. Historical wood—structure and properties. J. Cult. Herit. 13S, S5–S9.
Nishimura, T., 2015. Chipboard, oriented strandboard (OSB) and structural composite lumber. In: Ansell, M.P. (Ed.), Wood Composites. Woodhead Publishing, Cambridge.
Nishiyama, Y., 2009. Structure and properties of the cellulose microfibril. J. Wood Sci. 55, 241–249.
Nofal, M., Kumaran, K., 2011. Biological damage function models for durability assessments of wood and wood-based products in building envelopes. Eur. J. Wood Wood Prod. 69, 619–631.
Nourbakhsh, A., Ashori, A., Tabari, Z., Rezaei, H., 2010. Mechanical and thermo-chemical properties of wood-flour/polypropylene blends. Polym. Bull. 65 (7), 691–700.
Nóvoa, P.J.R.O., Ribeiro, M.C.S., Ferreira, A.J.M., Marques, A.T., 2004. Mechanical characterization of lightweight polymer mortar modified with cork granulates. Compos. Sci. Technol. 64, 2197–2205.
Olakanmi, E.O., Strydom, M.J., 2016. Critical materials and processing challenges affecting the interface and functional performance of wood polymer composites (WPCs). Mater. Chem. Phys. 171, 290–302.
Oliveira, V., Rosa, M.E., Pereira, H., 2014. Variability of the compression properties of cork. Wood Sci. Technol. 48, 937–948.

Oliver, C.D., Nassar, N.T., Lippke, B.R., McCarter, J.B., 2014. Carbon, fossil fuel, and biodiversity mitigation with wood and forests. J. Sustain. For. 33 (3), 248–275.
Ormondroyd, G.A., Stefanowski, B., 2015. Fibreboards and their applications. In: Ansell, M.P. (Ed.), Wood Composites. Woodhead Publishing, Cambridge.
Ormondroyd, G.A., Spear, M.J., Skinner, C., 2016. The opportunities and challenges for re-use and recycling of timber and wood products within the construction sector. In: Kutnar, A., Muthu, S.S. (Eds.), Environmental Impacts of Traditional and Innovative Forest-Based Bioproducts. Springer, Singapore.
Osburg, V., Starck, M., Toporowski, W., 2016. Consumer acceptance of wood-polymer composites: a conjoint analytical approach with a focus on innovative and environmentally concerned consumers. J. Clean. Prod. 110, 180–190.
Östman, B., Källsner, B., 2011. National Building Regulations in Relation to Multistorey Wooden Buildings in Europe. Växjö University, Växjö.
Pallardy, S.G., Kozlowski, T.T., 2008. Physiology of Woody Plants, third ed. Elsevier, Burlington, MA.
Pandey, C.N., Nath, S.K., Sujatha, D., 2011. Wood based panel products: technology road map. J. Indian Acad. Wood Sci. 8 (2), 62–67.
Panesar, D.K., Shindman, B., 2012. The mechanical, transport and thermal properties of mortar and concrete containing waste cork. Cem. Concr. Compos. 34, 982–992.
Papadopoulos, A.N., Traboulay, E., 2002. Dimensional stability of OSB made from acetylated Fir strands. Holz Roh Werkst. 60, 84–87.
Pereira, H., 2007. Cork: Biology, Production and Uses. Elsevier, Amsterdam.
Pereira, H., 2013. Variability of the chemical composition of cork. BioResources 8, 2246–2256.
Pereira, H., 2015. The rationale behind cork properties: a review of structure and chemistry. BioResources 10, 6207–6229.
Pereira, H., Tomé, M., 2004. Cork oak and cork. In: Burley, J., Evans, J., Youngquist, J.A. (Eds.), Encyclopedia of Forest Sciences. Elsevier, Oxford, pp. 613–620.
Perkins, W., 2014. Survey of International Tall Wood Buildings, Summary Report. Forestry Innovation Investment (FII) and Binational Softwood Lumber Council (BSLC), Vancouver; Surrey.
Pizzi, A., Lipschitz, L., Valenzuela, J., 2011. Theory and practice of the preparation of low formaldehyde emission uf adhesives. Holzforschung 48 (3), 254–261.
Plötze, M., Niemz, P., 2011. Porosity and pore size distribution of different wood types as determined by mercury intrusion porosimetry. Eur. J. Wood Wood Prod. 69, 649–657.
Poletto, M., Pistor, V., Zattera, A.J., 2013. Structural characteristics and thermal properties of native cellulose. In: van de Ven, T., Godbout, L. (Eds.), Cellulose—Fundamental Aspects InTech open.
Popescu, C.-M., Hill, C.A.S., 2013. The water vapour adsorption-desorption behaviour of naturally aged *Tilia cordata* Mill. wood. Polym. Degrad. Stab. 98 (9), 1804–1813.
Potthast, A., 2006. Raw material for pulp. In: Sixta, H. (Ed.), Handbook of Pulp. Willey-VCH, Weinheim.
Rainer, J.H., Lepper, P., Karacabeyli, E., 2004. Seismic performance of conventional wood-frame buildings. In: Proceedings of 13th World Conference on Earthquake Engineering, Paper No. 3195.
Ramage, M.H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D.U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P.F., Scherman, O., 2017. The wood from the trees: the use of timber in construction. Renew. Sust. Energ. Rev. 68, 333–359.
Raven, P., Evert, R., Eichhorn, S., 1999. Biology of Plants, sixth ed. WH Freeman, New York, NY.

Reculusa, S., Trinquecoste, M., Dariol, L., Delhaès, P., 2006. Formation of low-density carbon materials through thermal degradation of a cork-based composite. Carbon 44, 1298–1352.

Reddy, M.M., Vivekanandhan, S., Misra, M.M., Bhatia, S.J., Mohanty, A.K., 2013. Biobased plastics and bionanocomposites: current status and future opportunities. Prog. Polym. Sci. 38, 1653–1689.

Rio Merino, M., Santa Cruz Astorqui, J., Hernandez-Olivares, F., 2005. New prefabricated elements of lightened plaster used for partitions and extrados. Constr. Build. Mater. 19, 487–492.

Rosa, M.E., Fortes, M.A., 1988. Rate effects on the compression and recovery of dimensions of cork. J. Mater. Sci. 23, 879–885.

Rosa, M.E., Fortes, M.A., 1993. Water absorption by cork. Wood Fiber Sci. 25 (4), 339–348.

Rowell, R.M., 2005. Handbook of Wood Chemistry and Wood Composites. CRC Press, Boca Raton, FL.

Rowell, R.M., 2007. Chemical modification of wood. In: Stoyko, F., Debes, B. (Eds.), Handbook of Engineering Biopolymers—Homopolymers, Blends and Composites. Hanser Publishers, Munich.

Rowell, R.M., Pettersen, R., Han, J.S., Rowell, J.S., Tshabalala, M.A., 2005. Cell wall chemistry. In: Rowell, R.M. (Ed.), Handbook of Wood Chemistry and Wood Composites. CRC Press, Boca Raton, FL.

Roy, D., Semsarilar, M., Guthrie, J.T., Perrier, S., 2009. Cellulose modification by polymer grafting: a review. Chem. Soc. Rev. 38, 1825–2148.

Ruther, P., Time, B., 2015. External wood claddings—performance criteria, driving rain and large-scale water penetration methods. Wood Mater. Sci. Eng. 10 (3), 287–299.

Saheb, D.N., Jog, J.P., 1999. Natural fiber polymer composites: a review. Adv. Polym. Technol. 18, 351–363.

Saka, S., 2001. Chemical composition and distribution. In: Hon, D.N.S., Shiraishi, N. (Eds.), Wood and Cellulosic Chemistry. Marcel Dekker, New York, NY, pp. 51–82.

Salas, C., Nypelö, T., Rodriguez-Abreu, C., Carrillo, C., Rojas, O.J., 2014. Nanocellulose properties and applications in colloids and interfaces. Curr. Opin. Colloid Interface Sci. 19, 383–396.

Salthamer, T., Fuhrmann, F., 2000. Release of acetic acid and furfural from cork products. Indoor Air 10, 133–134.

Satyanarayana, K.G., Arizaga, G.G.C., Wypych, F., 2009. Biodegradable composites based on lignocellulosic fibers—an overview. Prog. Polym. Sci. 34, 982–1021.

Savory, J.G., 1969. Testing the fungus resistance of board materials. Mater. Organismen 2, 49–56.

Schut, J.H., 2007. First extrusion of complex WPC window profiles. Plast. Technol. Article 5, 1.

Schwarzkopf, M.J., Burnard, M.D., 2016. Wood-plastic composites—performance and environmental impacts. In: Kutnar, A., Muthu, S.S. (Eds.), Environmental Impacts of Traditional and Innovative Forest-Based Bioproducts. Springer, Singapore.

Schwarzkopf, M., Muszynski, L., 2015. Strain distribution and load transfer in the polymer wood particle bond in wood plastic composites. Holzforshung 69, 53–56.

Sen, A., Miranda, I., Pereira, H., 2012. Temperature-induced structural and chemical changes in cork from *Quercus cerris*. Ind. Crop. Prod. 37, 508–513.

Sen, A., van den Bulcke, J., Defoirdt, N., van Acker, J., Pereira, H., 2014. Thermal behaviour of cork and cork components. Thermochim. Acta 582, 94–100.

Sen, A., Pereira, H., Olivella, M.A., Vilaescusa, I., 2015. Heavy metals removal in aqueous environments using bark as a biosorbent. Int. J. Environ. Sci. Technol. 12, 391–404.

Shalbafan, A., Benthien, J.T., Lerche, H., 2016. Biological characterization of panels manufactured from recycled particleboards using different adhesives. BioResources 11, 4935–4946.

Sherman, L.M., 2008. Enchancing biopolymers: additives are needed for toughness, heat resistance & processability. Plast. Technol. http://www.ptonline.com/articles/enhancing-biopolymers-additives-are-needed-for-toughness-heat-resistance-processability.

Silva, S.P., Sabino, M.A., Fernandes, E.M., Correlo, V.M., Boesel, L.F., Reis, R.L., 2005. Cork: properties, capabilities, and applications. Int. Mater. Rev. 50, 345–365.

Silva, A.J.P., Lahr, F.A.R., Christoforo, A.L., Panzera, T.H., 2012. Properties of sugar cane bagasse to use in OSB. Int. J. Mater. Eng. 2 (4), 50–56.

Smook, G.A., 1992. Handbook for Pulp & Paper Technologies, second ed. Angus Wilde Publications, Vancouver.

Sommerhuber, P.F., Wang, T., Krause, A., 2016. Woodplastic composites as potential applications of recycled plastics of electronic waste and recycled particleboard. J. Clean. Prod. 121, 176–185.

Soucy, J., Koubaa, A., Migneault, S., Riedl, B., 2014. The potential of paper mill sludge for wood–plastic composites. Ind. Crop. Prod. 54, 248–256.

Spear, M.J., Eder, A.C., 2015. Wood polymer composites. In: Ansell, M.P. (Ed.), Wood Composites. Woodhead Publishing, Cambridge.

Stark, N.M., Rowlands, R.E., 2003. Effects of wood fiber characteristics on mechanical properties of wood/polypropylene composites. Wood Fiber Sci. 35, 167–174.

Stark, N.M., Cai, Z., Carll, C., 2010. Wood-based composite materials: panel products, glued-laminated timber, structural composite lumber, and wood–nonwood composite materials. In: Wood Handbook: Wood as an Engineering Material. General technical report FPL-GTR-190. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Stefanowski, B., Curling, S., Ormondroyd, G., 2015. The sorption of volatile organic compounds (VOCs) by modified MDF panels and the effects on mould colonisation and growth. In: Proceedings of the International Panel Products Symposium, BioComposites Centre; Bangor, UK, pp. 175–183.

Teuber, L., Osburg, V., Toporowski, W., Militz, H., 2016. Wood polymer composites and their contribution to cascading utilisation. J. Clean. Prod. 110, 9–15.

Thakur, V.K., Thakur, M.K., 2014. Processing and characterization of natural cellulose fibers/thermoset polymer composites. Carbohydr. Polym. 109, 102–117.

Thoemen, H., Irle, M., Sernek, M., 2010. Wood-Based Panels—An Introduction for Specialists. Brunel University Press, London.

Thomson, H., 2009. A Process Revealed. FUEL, London.

Uddin, N., Kalyankar, R.R., 2011. Manufacturing and structural feasibility of natural fiber reinforced polymeric structural insulated panels for panelized construction. Int. J. Polym. Sci. Article ID 963549, p. 7.

UPM ProFi profiled materials, 2016a. http://assets-upmprofi.upm.com/GLO_Brochures/.

UPM-ProFi-Facade-Technical-EN.pdf, 2016b. (6.06.2016).

Vahtikari, K., Silvo, J., Metsala, H., Paajanen, O., 2012. The development of wood floor construction in Finland. For. Prod. J. 62 (5), 388–394.

Wacker, J.P., 2010. Use of wood in buildings and bridges. In: Ross, R.J. (Ed.), Wood Handbook—Wood as an Engineering Material. General technical report FPL-GTR-190. Madison, WI, pp. 17.1–17.12.

Wang, S., Lu, A., Zhang, L., 2016. Recent advances in regenerated cellulose materials. Prog. Polym. Sci. 53, 169–206.

Wiedenhoeft, A.C., Miller, R.B., 2005. Structure and function of wood. In: Rowell, R.M. (Ed.), Handbook of Wood Chemistry and Wood Composites. CRC Press, Boca Raton, FL.

Winandy, J.E., Rowell, R.M., 2005. Chemistry of wood strength. In: Rowell, R.M. (Ed.), Handbook of Wood Chemistry and Wood Composites. Taylor & Francis, Boca Raton, FL.

Wolfe, R.W., Gjinolli, A., 1996. Cement bonded wood composites as an engineering material. In: Proceedings of the Use of Recycled Wood and Paper in Building Applications, Madison, WI.

Wood Panels Industry Federation, 2014a. Panel Guide Annex 2A: Particleboard (Wood Chipboard), Timber Research and Development Association; High Wycombe, UK.

Wood Panels Industry Federation, 2014b. Panel Guide Annex 2B: OSB (Oriented Strand Board), Timber Research and Development Association; High Wycombe, UK.

Wood Panels Industry Federation, 2014c. Panel Guide Annex 2D: Plywood, Timber Research and Development Association; High Wycombe, UK.

Wood Panels Industry Federation, 2014d. Panel Guide Annex 2E: Dry Process Fibreboards (MDF), Timber Research and Development Association; High Wycombe, UK.

Wood Panels Industry Federation, 2014e. Panel Guide Annex 2F: Wet Process Fibreboards, Timber Research and Development Association; High Wycombe, UK.

Wua, Q., Chi, K., Wub, Y., Lee, S., 2014. Mechanical, thermal expansion, and flammability properties of co-extruded wood polymer composites with basalt fiber reinforced shells. Mater. Des. 60, 334–342.

WWF, 2006. Cork screwed? Environmental and economic impacts of the cork stoppers market. WWF report May 2016.WWF/MEDPRO.

Xu, X., Yao, F., Wu, Q., Zhou, D., 2009. The influence of wax-sizing on dimension stability and mechanical properties of bagasse particleboard. Ind. Crop. Prod. 29 (1), 80–85.

Yang, H., Yu, L., Wang, L., 2015. Effect of moisture content on the ultrasonic acoustic properties of wood. J. For. Res. 26 (3), 753–757.

Yu, L., Dean, K., Li, L., 2006. Polymer blends and composites from renewable resources. Prog. Polym. Sci. 31, 576–602.

Zabalza Bribián, I., Usón, A.A., Scarpellini, S., 2011. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. 46, 1133–1140.

Zaborniak, R., 1989. Prediction of long-term density of cellulose fibre insulation in horizontal spaces of new residential houses. J. Build. Phys. 13, 21–32.

Zhang, S.Y., 1995. Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories. Wood Sci. Technol. 29, 451–465.

Zierdt, P., Theumer, T., Kulkarni, G., Däumlich, V., Klehma, J., Hirsch, U., Weber, A., 2015. Sustainable wood-plastic composites from bio-based polyamide 11 and chemically modified beech fibers. Sustain. Mater. Technol. 6, 6–14.

Zolfaghari, A., Behravesh, A.H., Adli, A., 2013. Continuous glass fiber reinforced wood plastic composite in extrusion process: mechanical properties. Mater. Des. 51, 701–708.

Nonwood bio-based materials

3

3.1 Introduction

L. Nunes
LNEC, Lisbon, Portugal
cE3c/ABG and University of the Azores, Azores, Portugal

Whilst the majority of bio-based building focuses on wood, the use of nonwood materials in the built environment is an area of growing importance. The wide range of uses of bio-based materials is summarised in Table 3.1.

This chapter will focus on the background and importance of nonwood bio-based building materials in the construction market and will review the properties, present and historic use, and the state-of-the-art research of the most relevant or innovative raw materials, in particular, flax, hemp, straw, bamboo and rattan, reed, wool, peat, grass and several pith plants.

Table 3.1 Examples of uses of bio-based materials within the construction sector (Berge, 2000)

Material	Typical uses
Wood (softwood and hardwood)	Structural construction (load bearing and nonload bearing), cladding (interior and exterior), flooring, roofing (shingles), doors and windows (interior and exterior), traditional connectors, insulation products, loose fibres, fibres in panel products, wood-plastic composites, cellulose (paper and pulp products) and chemicals for bioproducts
Straw, grass and reed	Roofing, wall constructions, wall cladding, insulation, cellulose products and chemicals
Bast fibres	Insulation, replacement for wood in panel products, fibre-plastic composites, filler in concretes, cellulose and chemicals
Grass turf and moss	Roofing and natural insulation
Peat	Wall construction and insulation

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00003-3
© 2017 Elsevier Ltd. All rights reserved.

3.2 Flax

R. Réh, M.C. Barbu†*
*Technical University in Zvolen, Zvolen, Slovak Republic
†University of Applied Sciences, Kuchl, Austria

3.2.1 Introduction

Flax (*Linum usitatissimum* L.) is an annual plant. It is probably the oldest textile fibre known to mankind, having been used since ancient times for the production of linen cloth. The common flax is an important economic plant used for the fibres obtained from its stem, which are converted into linen, thread and cordage and for the line seed oil, extracted from its seed; flax fibre is optimised for the production of thin strong fibres.

Flax grows in moderate climates (Fig. 3.1) and is presently cultivated, amongst others, in large parts of Western and Eastern Europe, in Canada and the United States, and in Russia, Argentina, India and China, with approximately 5 million ha. grown annually. Of this, approx. 3.8 million ha. are used for the production of linseed only, 0.2 million ha. for fibres only and approximately 1 million ha. for both linseed and fibres (Bos, 2004). In the traditional flax countries like the Netherlands, Belgium and France, the main focus of the flax production lies still on the apparel and home textile market. The main output from this production chain is the long fibres for spinning yarn (Fig. 3.2), where fibres are isolated from the plant via processes known as retting, breaking, scutching and hackling. These processes also produce short fibres as a by-product. Flax represents a potential alternative source of lignocellulosic raw materials, which could supplement wood from natural and plantation forests. In Europe, interest in agricultural materials has largely been driven by agricultural

Fig. 3.1 Field of ripe fibre flax.

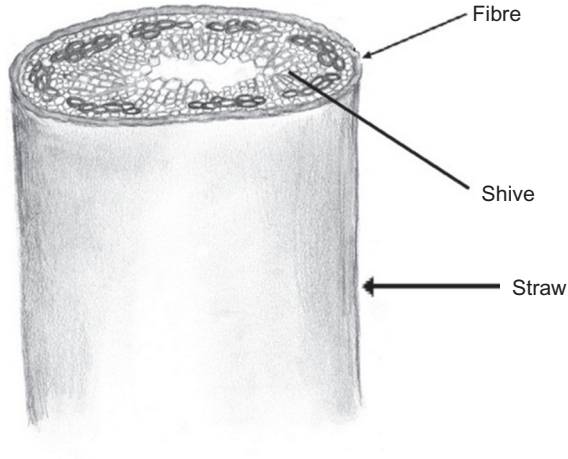


Fig. 3.2 Flax stem.

policy, which has encouraged farmers to devote land to the growth of nonfood crops rather than to food production. As a consequence, fibre crops including flax have received considerable attention during the last years of 20th century, and the forest product industries, with their huge demand for raw materials, have been identified as potential consumers of the crop materials (Hague *et al.*, 1998).

Flaxboard is produced from utilising shives from the flax plant left over from the linen industry. It is similar in some ways to particle board but has different properties and applications. It is not a particle board substitute and is generally required where thicker, low-density panels are an advantage (Barbu *et al.*, 2014). Flaxboard would normally be used where it would not be exposed to moisture and common usages including door cores, fire-check doors and partitions.

The technology of manufacture of flaxboard is different from that of producing particle board, since the flax shives are already particles and therefore chipping machines or mills are not necessary; however, the shives are thoroughly cleaned for removing dust, fibres and coarse particles. The shives come to the production plant with a low moisture content of 11%–14%—a fact that favourably influences the heat economy. The dust-free shives are fed into a machine, which removes fibres and fibre bundles. Subsequently, they pass a cyclone, a puffer silo and a pneumatic sorting device (Kollmann *et al.*, 1975).

Flax, a natural product with extremely high tensile strength, appeared promising as reinforcement for materials made from wood chips. They are fine rectangular-shaped particles of lignocellulosic material obtained by longitudinal division of the stalk of the flax plant during scratching of the retted flax. Although flax have since long been used in for instance particle board for building applications, only in the last decennia has a renewed interest to use bast fibres as reinforcement in plastic matrix composites arisen. The low elasticity of the flax fibres compared with other fibres such as wool and cotton (which is a disadvantage during the spinning process) is a prerequisite for their use in composites. One of the first uses in this field was linen fabric as reinforcement for

phenol resin for the construction of a Spitfire aircraft during World War II (Bos, 2004). More recent applications are found in modern cars like, for instance, several Mercedes models and other European cars, where nonwoven fibre mats are used commercially for interior panels, sometimes in combination with other agricultural fibres.

3.2.2 Morphology of flax fibres and shives

The multilayer composite structure of the flax fibre is presented in Fig. 3.3. The fibres are located within the stems, between the bark and the xylem. Around 20 bundles can be seen on the section of a stem, and each bundle contains between 10 and 40 fibres linked together by a pectic middle lamella. Each fibre is made of a thin external layer, called the primary cell wall, and a thick secondary cell wall, which is divided into three layers (S1, S2 and S3).

The cell walls are made of cellulose microfibrils laid in spirals around the fibre axis and embedded in a pectic matrix. In the secondary cell wall, the angle between the microfibrils and the longitudinal axis (called the 'microfibril angle') is about 10 degree.

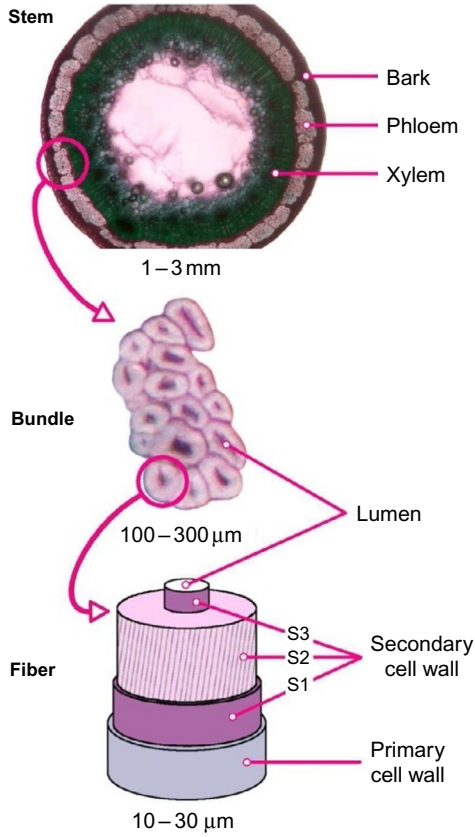


Fig. 3.3 Structure of flax: from the stem to the fibre (Charlet *et al.*, 2007).

In a flax bundle, the weight fraction of cellulose has been evaluated at 65%–75%, the noncellulosic polymers (i.e. pectins, hemicelluloses and lignin) at 20%–25% and water at 8%–10% (Aslan *et al.*, 2012). Considering the microstructural arrangement, the cellulose microfibrils act as the reinforcement of the pectic matrix, and the interface between these two materials is mainly composed of hemicelluloses (Charlet *et al.*, 2007).

The development of fibres is directly linked to the growth of the stem. It can be separated into three stages: the first stage corresponds to the elongation of the thin primary cell wall, from a few millimetres to several centimetres. The second stage begins with the centripetal synthesis of the secondary cell walls: first the S1 layer, then the main S2 layer and lastly the S3 layer. Growth is complete when the fibre is mature. During the lifetime of a cell, the centre of the fibre is filled with the cytoplasm; after the death of the cell, this empty space is called 'lumen'. Its section, which depends both on the perimeter of the primary cell wall and on the thickness of the cell walls, represents <10% of the entire fibre section (Charlet *et al.*, 2007).

The extraction of fibres from the stem is achieved in several steps. At first, the flax is dew retted. This means that the stems are pulled up and laid on the ground for 6–8 weeks so that natural microorganisms ingest the pectic cement and isolate the bundles from the xylem and the bark. Then, the stems are mechanically scutched, in order to eliminate shives and short fibres. Finally, the long tows can be hackled to separate the bundles, align the fibres and form a continuous tape. This tape can then be manually or enzymatically treated to extract the single fibres (Aslan *et al.*, 2012; Charlet *et al.*, 2007).

Fig. 3.4 shows a cross section of the flax stem. The bundles, which are used for textile and technical applications, are located just under the skin and embedded in bast tissue (Bos, 2004). Flax fibres, unlike artificial counterparts, are not continuous, but they have a composite-like hierarchically organised structure. The bundles are between 60 and 140 cm long, and their diameter ranges from 40 to 80 µm. Each bundle

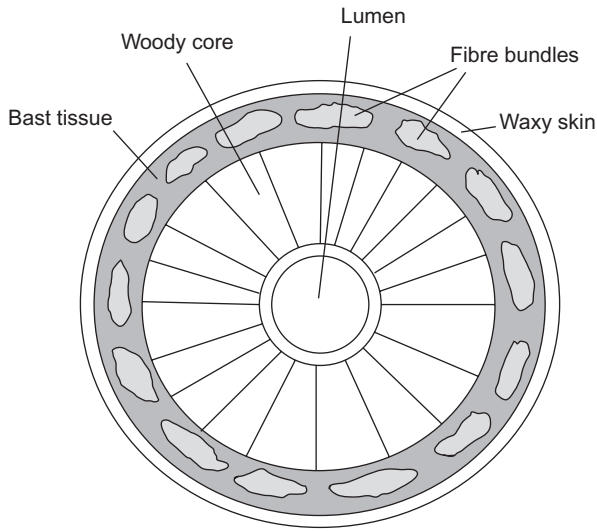


Fig. 3.4 Schematic representation of a stem cross section of the flax plant (Bos, 2004).

consists of 10–40 spindle-shaped single (elementary) fibres of 1–12 cm length and 15–30 µm diameter (Müssig and Stevens, 2010). The decomposition temperature of flax fibres is above 200°C, whilst they lose their strength after long exposure to the sunlight. They are amongst the strongest in the group of naturally occurring fibres (55 cN/tex and about 20% stronger in wet state), but they do not stretch much, with an elongation at break of only 1.8%.

3.2.3 Application of flax for building materials

Flax is amongst the strongest natural fibres, and its household history is long and rich, dating back 30,000 years. Classified as a bast fibre, it is a complex assembly of different polymers, polysaccharides such as cellulose, hemicelluloses and pectin and the phenolic-derived lignin. However, what distinguishes flax from other fibres and ensures its biological activity is a wide group of secondary metabolites derived from the phenylpropanoid pathway (Bledzki *et al.*, 2002). With such a complex structure, it comes as no surprise that there are many factors determining properties, and any alteration in one of those factors has an impact on fibre quality and quantity, influencing its most valued properties: tensile strength, absorptivity and biological activity.

Recently, there has been a decline in traditional uses of flax, partly due to its poor elasticity, time-consuming straw processing and the sensitivity of the crop to various biotic and abiotic factors. Nowadays, due to a growing demand for natural fibres, prospective applications of flax fibre have emerged in biocomposites, bioremediation, biofuels and medicine with these opportunities enhanced through selective growing programmes. It is expected that a better understanding of the genes involved in flax productivity and quality and an increased knowledge of cell-wall development in relation to properties will provide improvements via novel tools, such as molecular breeding, leading to more diverse products based on flax fibres (Preisner *et al.*, 2014).

Traditional flaxboard is an engineered panel material in which shives from the stalk of the flax plant are bonded together with a synthetic resin adhesive. Flaxboard is defined in standards as a particle board containing at least 70% flax and can also contain other raw materials such as particles of wood (wood, flakes, chips, shavings, saw dust and similar materials). The flaxboard industry in Europe dates from the late 1950s and until recently was only available in standard panel sizes because it was produced by daylight presses. Now, the technology has developed to produce a continuous panel in various lengths, which enables it to be cut into many possible sizes without wastage.

Flax shives from the stalk of the flax plant comprise the bulk of flaxboard and are prepared in a mechanical chipper. These chips are compressed and are generally bound together with synthetic resin systems such as urea–formaldehyde (*UF*) or melamine–urea–formaldehyde, though phenol–formaldehyde and polymeric methylene di-isocyanate (*PMDI*) are used by some manufacturers. The binding system employed depends on the end use intended and the grade of the product. The most common resin employed is UF, but this is only suitable for use in dry conditions.

Fig. 3.5 Traditional flaxboard.

The other three resin systems, mentioned above, confer a measure of moisture resistance to the composite (http://wpif.org.uk/uploads/PanelGuide).

Flaxboard can show excellent properties and offers numerous benefits; it can have smooth, sanded surfaces similar in appearance to particle board if required (Fig. 3.5), by increasing the panel density at the faces by the use of small particles of wood with a larger percentage of resin binder compared with the core of the panel. It is a lightweight panel and has natural characteristics that aid fire resistance. Although flaxboard is similar in some ways to particle board, it has different properties and applications, and so users should check technical performance data against the intended end-use application. Generally, flaxboard has a pale straw colour.

Panel density (and therefore panel mass) varies depending upon the thickness and end use. Typical densities are 350–600 kg/m^3. Panel sizes (length × width) commonly available are 2440 (2750 and 3660) × 1220 mm in thicknesses from 12 up to 60 mm. Other sizes are available or can be produced to order (http://wpif.org.uk/uploads/PanelGuide). Panels are produced with either square or postform edges.

The special properties of flaxboard have several advantages in a wide range of nonload-bearing applications. Its lightweight properties and natural characteristics, which aid fire resistance, make it a natural choice for fire-resistant door cores and partitions. Different grades of the product are available for different environmental conditions, ranging from general-purpose panels for use in dry conditions (for filling purposes and veneering) to nonload-bearing panels for use in humid conditions. The higher grades also find use for interior fitment (including furniture and worktops). Flaxboard can also find uses for acoustic doors and partitioning, packaging in the form of protection panels and profiled pack bearers, table tennis tables, warehouse shelves and worktops.

Careful storage and handling is important to maintain panels in their correct condition for use; therefore, flaxboard must be protected from rain and accidental wetting. During transport, it is particularly important to keep edges well covered. Panels should be stored flat in an enclosed, dry building. When handling panels, the edges and corners should be protected against damage. Flaxboard can be cut by a hand saw or power saw and machined (routed, spindled, planed and bored) with normal woodworking machinery. Tungsten carbide cutting edges are recommended for use with power tools.

There exist a lot of publications dealing with the possibilities of flaxboard fire-retardant treatments (Réh and Osvald, 1996; Zhang, 2011; Zhang *et al.*, 2012 and others).

Flax fibre is also being used to produce mineral-based composites or to reinforce cement or plaster. The use of low-embodied-energy materials such as flax is helping to create new market opportunities (http://www.stemergy.com).

The use of flax (and other) fibre composites is expected to make large inroads into home and commercial construction products in the coming years. The applications are numerous, and flax fibre composites can help innovative companies achieve their goals of implementing sustainable and environmentally sound building practises that are both cost-effective with superior features (Bledzki *et al.*, 2002). Some of the products that are in the works include panel materials and alternatives to wood-based panels such as flax plywood. New systems for blending flax fibre with concrete and stucco are already in place (Fig. 3.6). Flax insulation is available in Europe and soon to be available in North America (Mohanty *et al.*, 2005).

Because energy efficiency in buildings will be evaluated not only upon heating demand but also on primary energy demand, the ecological properties of the building materials for the whole assessment have become essential. This has been considered in research of bast fibres, such as flax, as raw materials of thermal insulations (Kymäläinen and Sjöberg, 2008; Korjenic *et al.*, 2011; Schmidt *et al.*, 2004 and others). The effect of treatments on the physico-chemical characteristics of shives and subsequent physical and mechanical properties of cementitious composites has been investigated by Khazma *et al.* (2014), whilst the effect of fibre treatments on the rheological properties of cement mortar was studied by Chafei *et al.* (2015).

3.2.4 Other applications of flax fibres

A rapidly expanding application for flax fibre is as a reinforcement and filler in the production of flax fibre composites. The binding materials range from thermoplastics such as polypropylene to thermoset resins such as polyester or polyurethane. Typical applications include automotive interior substrates, furniture and other flax-fibre-based consumer products. The properties of flax composites and their adaptations are reported by Tröger *et al.* (1998), Papadopoulos and Hague (2003), Kalia *et al.* (2009) and others.

Fig. 3.6 Product example of flax bio-based building materials.

Many of the technologies developed for automotive applications can be used to make consumer products from flax fibre composites (Clemons, 2002). It is possible to use compression moulding, injection moulding, simple hand lay-ups or hybrid technologies to produce consumer goods. Such products include furniture (chair backs or seats), sporting goods and- recreational products, luggage, musical instruments and sound reinforcement gear; in the future, more innovative products may result.

In many applications using glass fibre, flax may prove to be an efficient substitute.

3.2.5 Conclusion

In the era of volatile and rising oil and energy prices and with changing environmental standards affecting traditional materials, the future is bright for flax fibre composites. The growing demand for flax has and will continue to spur on innovation at all levels of the value chain. This will occur all the way from advancements in plant breeding to improve fibre yields and properties through to process and conversion technology optimisation based around flax fibre composites.

3.3 Hemp

R. Réh, M.C. Barbu†*
*Technical University in Zvolen, Zvolen, Slovak Republic
†University of Applied Sciences, Kuchl, Austria

3.3.1 Introduction

Hemp (*Cannabis sativa* L.), most likely based from Old English *hænep*, is an ancient plant that has been cultivated for thousands of years. It is a multipurpose crop delivering fibres, shives and seed. The fibre is used today for cigarette paper, insulation material and biocomposites. The shives, the woody inner core of the stem, are used for animal bedding and materials for construction. Through the Middle Ages and until the end of the sailing-ship period, hemp was an important crop in many European countries like the United Kingdom, France, the Netherlands, Germany, Spain and Italy; important applications for the strong fibre were canvas for sails, sacks, canvas water hoses and fabrics as well as ropes (Barbu *et al.*, 2014).

Today, hemp is a niche crop, cultivated on 10,000–15,000 ha. in the European Union. Because of its unique properties, particularly its environmental benefits and the high yield of natural technical fibres, hemp is a valuable crop for the bio-based economy (Carus *et al.*, 2013). China has the largest hemp acreage in the world, with approximately 1.3 million ha. of industrial hemp planted. Chinese dry industrial hemp-stalk output may reach 10 million tons/year. Because it is possible to make 1 m^3 of wood-based panel (at a panel density of 750 kg/m^3) from 1 ton of hemp stalks, if 50% of industrial hemp stalks were used to make hemp-stalk-based panels,

5 million m^3 of industrial hemp-stalk-based panels could be produced per year in China (Li *et al.*, 2014a,b).

Hemp cultivars and growth hemp (Figs 3.7 and 3.8) belong to the Angiosperm phylum since it has vessel elements in the woody core (xylem) like hardwood. It belongs to the eudicotyledons like hardwoods, numerous bushes and herbs, since it has two cotyledons (i.e. seed leaves). The long and flexible hemp fibres are embedded in the bark (cortex) on the surface of the stem (Thygesen, 2006).

Hemp yields a long, strong fibre that cannot be replicated by fibres from other plants, such as cotton, flax, jute, kenaf or ramie. Industrial hemp is potentially useful

Fig. 3.7 Hemp field with mature hemp plants.

Fig. 3.8 Hemp stem.

in a number of industries, for example, textiles (Soljacic and Cunko, 1994; Zhang *et al.*, 2009), composites of high strength (Sawpan *et al.*, 2011), fibreboard (Pecenka *et al.*, 2009), heat-insulating materials (Yates, 2006) and nonwood lignocellulosic composites (Barbu *et al.*, 2014). A detailed study of literature sources on the use of nonwood plant fibres including hemp for composite (sheet) structural materials was compiled by Youngquist *et al.* (1994).

The hemp shiv is a by-product that is usually burnt in fields as trash after the hemp fibre has been harvested. The volume of the shiv is twice that of the fibre and four times more than seed; finding a use for the hemp shiv will be a key factor in promoting the development of the hemp industry.

Wood costs are generally rising as demand surpasses supply, which increases opportunities for materials such as hemp (Pecenka *et al.*, 2010). Therefore, determining the feasibility of using industrial hemp for the manufacture of composites based on the characteristics of the raw materials is of great importance. Studies have been performed, examining the feasibility of using hemp shives in the manufacture of lightweight construction board (Schopper *et al.*, 2009) and particle board (Theis and Grohe, 2002; Nikvash *et al.*, 2012). The option of replacing wood chips with hemp shives in the production of particle board was considered by Dix *et al.* (2009), who reduced the density of triple-layer particle board by using hemp shives from 650 to 400 kg/m^3. Proposals of modification of the particle board core layer with hemp shives were described by Réh and Vrtielka (2012) and Li *et al.* (2014a,b), whilst a novel low-density sandwich panel made from hemp was produced by Selinger and Wimmer (2015).

3.3.2 Morphology of hemp fibres

The stem of hemp (Fig. 3.9) typically has a diameter from 0.6 to 4.5 cm, depending on various factors, such as sowing date, plant density, species and soil. Hemp fibres are present in bundles as long as the stems, which can easily be peeled off the xylem, either manually or mechanically. The outer layer of the stem, the epidermis, is covered by a 2–5 µm surface layer cuticle, which has a wax to protect the plant from drying as well as colour-binding media and stomata (pores) through which the plant ventilates and regulates evaporation. The cortex layer is a thin layer of walled cells that has no fibre but does contain chlorophyll (Thygesen, 2006).

Phloem layer contains short cells that have chlorophyll and long cells that are bast fibres. Phloem layer consists bundles of 100–300 polygonal-shaped primary and secondary fibre cells with four to six sides. Both are thick walled, with a high content of cellulose and a low content of hemicellulose and lignin. About 92%–95% hemp fibres are from the primary cells. The thickness of the cell wall in primary and secondary cells is about 7–13 and 3–6 µm, respectively, whilst the average length in primary and secondary fibre cells is about 20 and 2 mm, respectively. The secondary fibres are more brittle than the primary fibres. The cambium layer (10–50 µm) is the growth area, which produces hurds on the inside and bast and bark on the outside (Dai, 2012). Although this is a differentiation layer, it is also an abscission layer where fibres and hurds separate during the retting/breaking process. The xylem is a

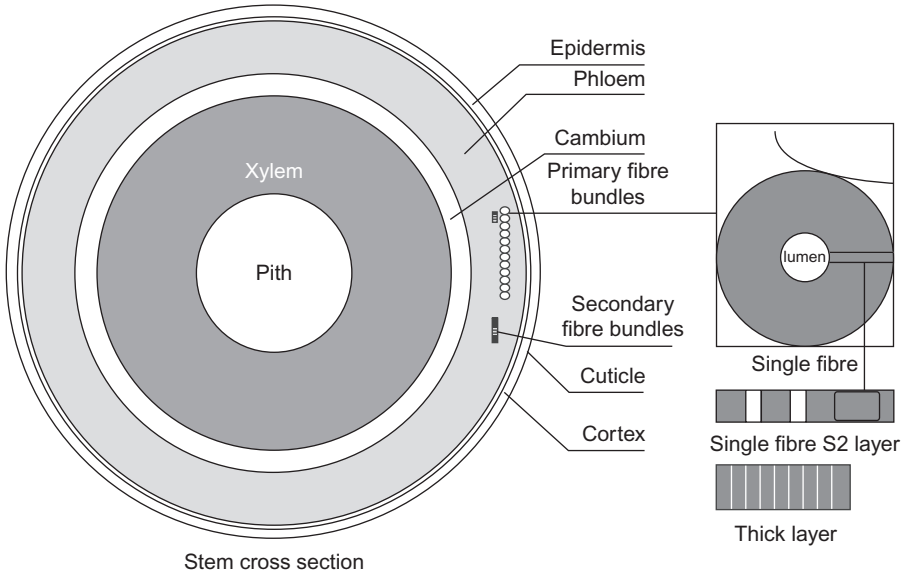


Fig. 3.9 Model of transverse hemp stem section zooming to single fibre, secondary cell wall and finally the cell-wall lamella (Dai, 2012).

hollow cylinder of 1–5 mm thick at the centre of the plant and exists throughout the stem except at the joints. It consists of empty and dead cells with thickened sidewalls. The pith layer is an empty space composed of thick and woody tissue used to support the plant. The product from this area is called hurds, which comprises 60%–75% of the total pith mass.

The microstructure of the hemp-fibre wall includes middle lamellae (30–50 nm), primary wall (70–100 nm) and a secondary cell wall, which was composed of a 100–130 nm thin S1 layer and a 3–13 µm thick S2 layer. Observations (Fig. 3.10) showed that the S2 layer had a laminate structure of 1–4 concentric layers of 1–5 µm in thickness. These layers were constructed of 100 nm thick lamellae. Thin layers of 200–240 nm in thickness were located in between the concentric layers. These thin layers seem to lack cellulose. The microfibril angle can strongly influence mechanical properties such as tensile strength and modulus (Dai, 2012).

As shown in Fig. 3.11, the microfibril angle in S1 layer of hemp is in the range of 79–90 degrees compared with 25–30 degrees in the outer part of S2 layer and 0–5 degrees in the inner part of S2 layer (Thygesen, 2006; Dai, 2012). The distribution of lignin, pectin and waxes in the cell wall varies between different cell walls and layers. The inner part of secondary wall contained less lignin, whilst the outer part contained the same amount of lignin as the middle lamellae. Both the parenchyma cells and the single-fibre compound middle lamellae contained pectin, whilst the secondary wall lacked pectin. Wax could be found in the epidermis cells with highest content in the cuticle layer. According to the histochemical investigation, pectin degradation can provide separation of the fibre bundles from the xylem surface, whilst separation of

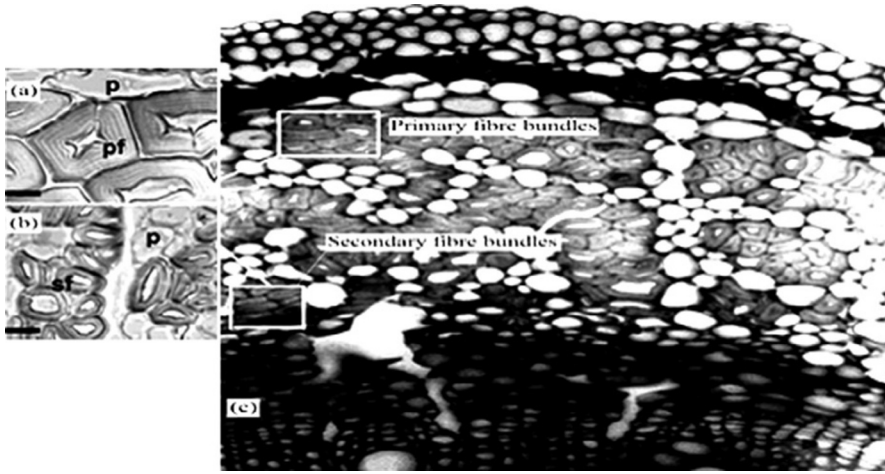


Fig. 3.10 Structure of hemp fibre bundles in phloem layer: (A) primary fibre bundles, (B) secondary fibre bundles and (C) cross section of hemp stem (Dai, 2012).

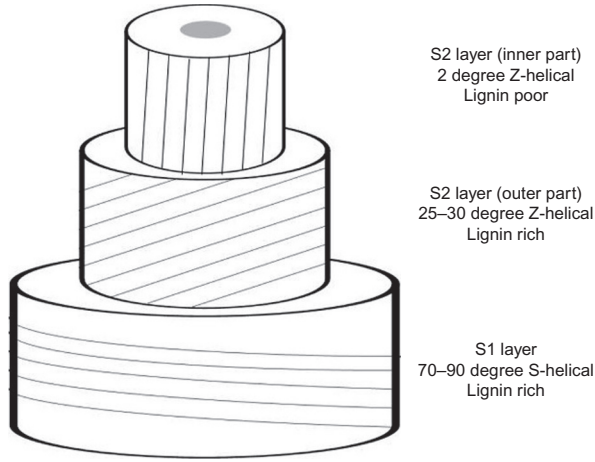


Fig. 3.11 Model of the microfibril orientation throughout the secondary cell wall (the S3 layer was not found in hemp fibres) (Dai, 2012).

the fibre bundles into single fibres requires both lignin and pectin degradation. Wax can inhibit binding between fibres and resin.

The single hemp fibres are bonded together with pectins and small amounts of lignin to create the next microstructural level, the technical fibres, with diameters of 50–100 mm (Dai, 2012). These filaments are fixed together with a pectin–lignin matrix that forms bundles in the cortex of the plant stems. Thus, bast fibres are bundles of individual strands of fibres held together by a pectin–lignin interface.

3.3.3 Applications of hemp fibres for building materials

Each part of the industrial hemp plant has its useful application. The hemp stalk consists of long and sturdy fibres; the inner core has moisture absorption and insulation properties; the seed is a source of oil and protein. Hemp possesses three characteristics that are useful in the construction industry: its insulation capacity, the mechanical resistance of the fibres and low density (110 kg/m^3). Additionally, hemp shives can also absorb a large quantity of water (3.5–5 times their own weight). Hemp will remove CO_2 from the atmosphere less than 12 months before the material is embodied within the structure of a building (Lawrence, 2015).

The most rapidly expanding application for hemp is as reinforcement in composites. The blending materials range from thermoplastics such as polypropylene and polyethylene to thermosets such as polyester. The common application is to blend hemp with polypropylene in a nonwoven (felt) mat that is compression moulded to form a three-dimensional part (Barbu *et al.*, 2014).

Hemp is a basic ingredient for ecological building materials. Because of the many possibilities offered by these crops and their relatively easy cultivation, there is renewed attention given to hemp use. Both the stalks and the fibres are processed into construction materials.

Housing insulation made from hemp is quickly becoming a popular eco-friendly alternative to traditional insulation material like mineral wool. Not only is hemp a more sustainable raw material, but also the final product is carbon-negative. That means it has the ability to absorb more greenhouse gases over its lifetime than emitted during the production process. The production of mineral wool, on the other hand, contributes greenhouse gases to the atmosphere. A recent study compared the two insulation materials and concluded that hemp was the more sustainable choice (Ventura *et al.*, 2012).

The use of hemp fibre is expected to make large inroads into home and commercial construction in the years to come. The applications are numerous, and hemp can help innovative companies achieve their goals of implementing sustainable and environmentally sound building practises that are both cost-effective and affordable. Some of the products that are in the works include panel materials, utilising hemp and environmentally friendly binders as an alternative to wood-based panels such as plywood.

Hemp has also found its way into concrete mixes. Hemp concrete can be used for a variety of construction needs, from walling to roof insulation to flooring. On top of being carbon-negative, hemp concrete is said to be easier to work with and has natural insulating and moisture-regulating properties. Hemp bricks also lack the brittleness of traditional concrete and thus do not require expansion joints.

Fibre-reinforced polymer composites consist of two main components: reinforcing fibres and a polymer matrix. The most commonly used composite in the construction industry is glass-fibre-reinforced polymer, which in building construction is mainly used in structural and architectural applications such as roof construction, door frames, canopies, dormers, chimneys and coping systems (Fig. 3.12). Natural-fibre-reinforced polymers offer a potential alternative to glass-fibre products and

Fig. 3.12 Hemp particle board.

could prove to have a lower embodied environmental impact (Dammer *et al.*, 2013). Some other benefits of processing with natural-fibre-reinforced polymers include lowered abrasion to machinery and potentially lower impact of human respiratory system.

The density of natural fibres (1.5 g/cm^3) is significantly lower than that of glass (2.5 g/cm^3). The weight of a material is a key consideration in application as a lower-density material can reduce costs in some areas of manufacture, fabrication, transportation and construction. The low density of natural fibres also results in a lower thermal conductivity in certain configurations, suggesting that natural-fibre-reinforced polymers could perform well where thermal bridging is a concern, such as window frames or secondary structural elements such as wall ties.

Hemp fibre is also being used to produce mineral-based composites, in much the same way polypropylene or glass fibre is used to reinforce cement or plaster. Hempcrete (lime-hemp mixture) is used as plaster material or as construction material, depending on the composition of the mix. A thick layer of hempcrete on cold, thick walls can raise the comfort of a home significantly. A coat of 4–6 cm ensures the thermal regulation of the wall and can also correct unevenness. The inertia of the wall is maintained, and the moisture balance is not disturbed. The introduction of a lime-hemp mix to the inner side is a technique that is applied in the renovation of old buildings.

As a construction material, hempcrete combined with a timber frame can be used for walls, roofs and floors, each with a slightly modified compound. It can also be applied to the outer side of an existing home as outer wall insulation. The lime-hemp mix is applied by spraying, deposited in a sliding casing or built with prefab pressed bricks. The outer walls can then be finished with a coated wooden cover or with a plaster mix of lime and sand.

A case has shown that hempcrete houses score at least as good as traditional brick constructions when it comes to constructive lifespan (Stanwix and Sparrow, 2014). It has also shown that the energy consumption for heating is the same in hempcrete

houses as in traditionally built homes. There is less condensation in the lime-hemp houses, and there are less cold bridges as well. The use of prefabricated hempcrete blocks is the same as traditional way of building with bricks at the construction site. Hempcrete blocks are laid with plaster or lime and finished with plaster or lime (brush and spraying machine). The larger bricks can also be laid on shingles as floor filling. The bricks have high fire-resistance properties; they spread no flames, maintain their mechanical properties and create little smoke.

3.3.4 Conclusion

Hemp fibre, as with many other natural fibres, is undergoing a renaissance within the construction sector. This is as a result of not only its inherent properties but also the environmental benefits in terms of energy saving during construction phases. As technology improves, more products will enter the marketplace, with processes and techniques from other industries such as the automotive industry becoming more commonplace within the construction sector. Amongst the key factors that will allow this to happen are

- cost-effective
- high tensile strength and stiffness
- ideally suited for needle-punched nonwoven products
- effective replacement for glass fibre
- reduces moulding time
- weight reduction in finished part
- easy to process and recycle
- can be customised to meet a variety of specifications and different manufacturing systems
- consistent quality and availability of supply is possible

3.4 Straw

P. Walker[*,†], *A. Thomson*[*], *D. Maskell*[†]
*BRE Centre of Innovative Construction Materials, Garston, United Kingdom
†University of Bath, Bath, United Kingdom

3.4.1 Structure and composition of straw

Straw stems from cereal crops such as wheat, barley, oats, rye and rice are composed of nodes and internodes (Fig. 3.13). The plant's leaves grow from the nodes, with the internodes comprising hollow connecting tubes. Around 90% of cereal crop straw is formed from cellulose, hemicellulose and lignin, with water-soluble elements and ash, including silica, making up the remaining constituents (Harper and Lynch, 1981). The silica content, higher in rice straw, aids durability of the straw. Over the

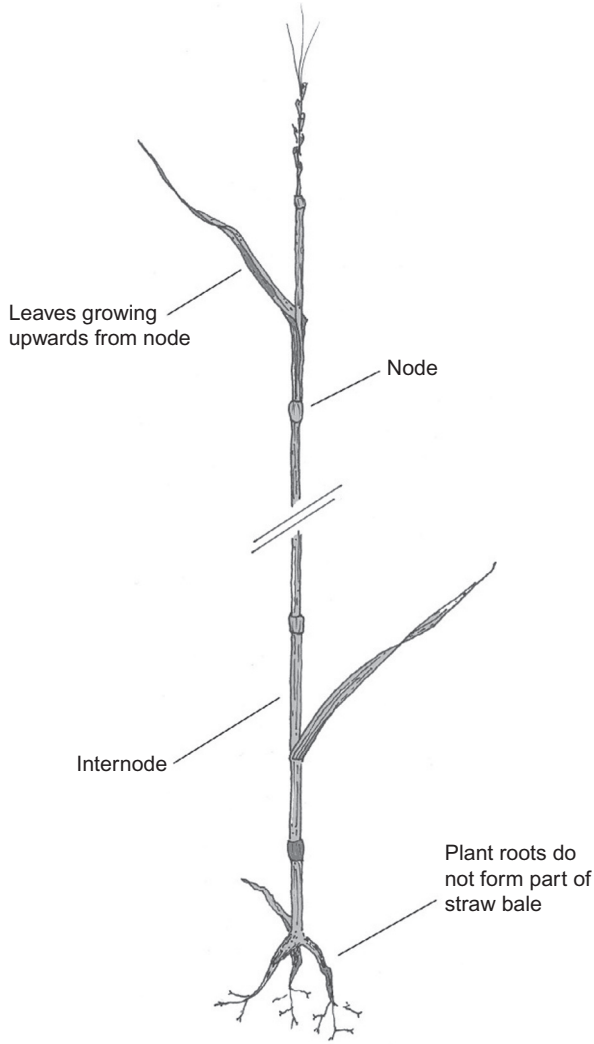


Fig. 3.13 Straw structure.

past 100 years, crops have been cultivated for an increased cereal yield. This has generally resulted in shorter straw stems due to the tendency of longer varieties to collapse in the field. This has increased the risk of fungal growth on the cereal, and as a result, modern wheat straw is typically around half the height of traditional varieties. In Europe, wheat straw is widely preferred for applications such as straw-bale building, as it is readily available and has fewer other higher-value-added uses. However, in other parts of the world, straw from rice crops is preferred for its durability.

3.4.2 Straw bales as a construction material

Straw has probably been used for construction since the dawn of agricultural societies. Historical uses have included roofing (thatch), substrates for plasters, bio-aggregates to clay and lime plasters and as loose floor covering. In modern construction and thatching, straw is still used not only as an bio-aggregates to clay and lime materials but also as raw material for compressed straw products, such as STRAMIT, and since the late nineteenth as insulation in bale form (King, 2006).

Traditional rectangular straw bales, measuring around $1 \times 0.45 \times 0.35$ m and weighing around 20 kg, form ready-made low-density building blocks suited to laying in courses as large masonry blocks. The bales are generally laid dry, without bonding mortar, relying on internal pinning and vertical precompression for stability during construction. Though straw bales can be used for load-bearing walls in low-rise applications, the primary building benefit of straw bales is derived from their beneficial insulating qualities. A 500 mm wide wall has a thermal transmittance (U-value) around 0.13–0.20 W/m^{2}K.

Laid horizontally and lengthwise, traditional bales form walls around 500 mm thick once plastered. External coatings are typically lime or weak cement: hydrated lime mixes with internal plasters either lime or clay based. King (1996) has likened plastered straw-bale walling to structural insulated panels (*SIPs*); like straw-bale walling, SIPs have two structural skins separated by lightweight insulation (Kermani, 2006). As an alternative to wet-applied coatings, straw bales may be dry lined with oriented strand board (*OSB*), high-density wood fibre sheathing board or cross-laminated timber.

In common with other renewable building materials, straw requires carbon dioxide for growth and thus through the process of photosynthesis stores around 1.35 kg of carbon dioxide for every 1.00 kg of straw (Sodagar *et al.*, 2011). Straw is widely available and is a very affordable building material. Unlike many other crop-based building materials, such as hemp and flax, it is a coproduct of preexisting essential food production. Straw-bale buildings can now be found in all major inhabited continents. When used appropriately, straw will provide a long-lasting durable insulation material. One of the oldest surviving examples of straw-bale construction in Europe is the Feuillette House (Lamarche, 1921), built in 1921 in Montargis, France (Fig. 3.14). However, prolonged exposure to damp or excessively humid conditions can cause straw to degrade.

There are currently three main straw-bale wall-building applications: load-bearing walls, nonload-bearing in situ walls and prefabricated panel construction. Each of these techniques is briefly outlined below (Figs 3.15 and 3.16):

- Initial uses of straw bales were in low-rise load-bearing walls. Using the bales to carry vertical loads and resist lateral forces is a resource-efficient use of the material, as it avoids the need for a separate structural frame. In this method, bales are stacked into a low-density biomasonry wall. Some form of vertical prestress is normally applied to stabilise the wall and remove initial deformation ahead of plastering and loading (Jones, 2009). Load-bearing straw-bale walls are generally plastered, and research has confirmed that it is the composite

Fig. 3.14 Feuillette House, Montargis, France (built in 1921).
Reproduced with permission from Reseau Francais de la Construction Paille.

Fig. 3.15 BaleHaus at the University of Bath, United Kingdom.

of the plaster coats, restrained by the straw bales, that provides the primary load resistance (King, 2006; Vardy and MacDougall, 2006).

- Nonload-bearing straw-bale construction takes advantage of straw's thermal insulation properties but uses an additional structural system for support. This approach reduces risk, as the structural integrity of the building is no longer dependent on the straw, and allows in situ construction to readily proceed under cover.
- In recent years, prefabricated straw-bale construction has become increasingly common. Panels most commonly use timber frames fabricated off-site to minimise some of the risks (fire and wet-weather damage) of using exposed straw on site. Prefabricated panel construction has opened up straw to a more mainstream market and produced products that can be certified and warranted.

Fig. 3.16 Straw-bale cladding panels at the eco-depot project (ModCell®).

3.4.3 Hygrothermal properties of straw bales

Although the thermal resistance of straw is not as high as other insulation materials, through their relative thickness (450–500 mm), straw-bale walls provide excellent thermal insulation. However, in addition to basic thermal resistance, straw, in common with many other bio-based building materials, also responds to changes in relative humidity. This hygroscopic behaviour means that the weight of straw at 90% *RH* is around 20% higher than when it is at 30% RH (at 20°C). Isotherms define the moisture adsorption response of different materials in response to increasing and decreasing levels of RH. Isotherm data for straw have been reported by Lawrence *et al.* (2009), Carfrae (2011) and Hedlin (1967) and are summarised in Fig. 3.17. The isotherm response is also dependent on temperature; most reported tests have taken place between 20°C and 23°C. Although straw-bale walls are still most commonly rated by their static U-value (thermal transmittance), an in-depth understanding demands more complex dynamic hygrothermal (heat and moisture) modelling.

Straw bales are orthotropic. As a result of the bale compaction process, straws are preferentially orientated to lay (rather randomly) perpendicular to the direction of compaction (also the longest dimension of the bale). Thermal conductivity is around 25% lower when measured lengthwise through the bale (i.e. in the direction of compaction), as compared with values measured across the direction of compaction. Tests at the University of Bath (Shea *et al.*, 2013) have confirmed that, for typical range of bale densities (60–140 kg/m^3), thermal conductivity of straw bales is relatively insensitive to variations on degree of compaction. A least-square regression analysis indicates that straw bales have a thermal conductivity across the direction of compaction of 0.064 W/mK at a density of 120 kg/m^3. Straw thermal conductivity also varies with moisture content, increasing with increasing moisture content (Shea *et al.*, 2013).

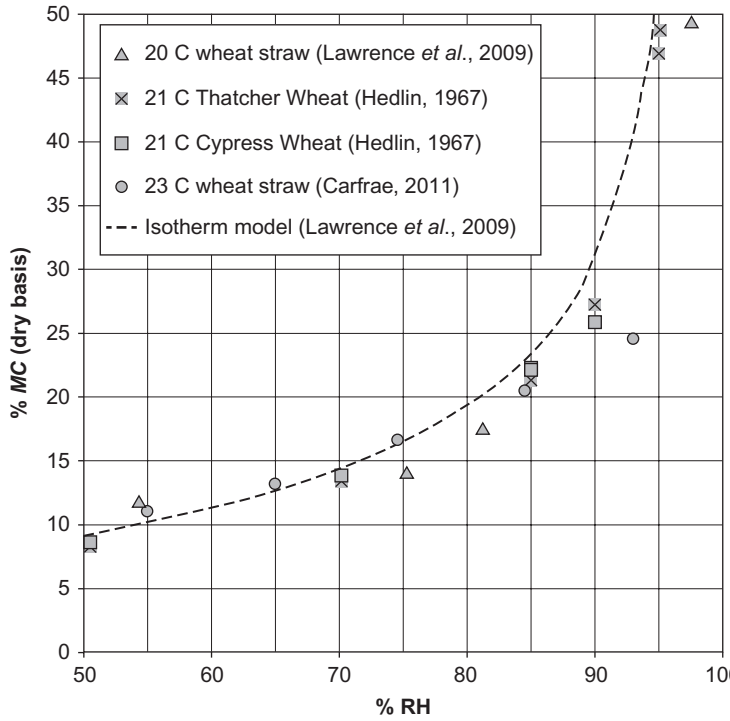


Fig. 3.17 Isotherms for wheat straw.

Degradation can occur through mould or microflora growth on the straw. The Fraunhofer Institute of Building Physics has described the different boundaries at which varying degrees of mould growth will initiate on wheat straw (Sedlbauer *et al.*, 2011). The findings of the study were presented using a graphical isopleth system, which provides a simple guide to climatic conditions that can support mould growth on wheat straw and is shown below in Fig. 3.18. However, whilst the isopleth can be helpful to assess the risk of deterioration, it does not necessarily indicate likely longer-term durability of straw (Thomson and Walker, 2013). Thomson and Walker (2014) found that when straw is kept in a high-humidity environment initial mould growth is observed but, after approximately 6 days, this growth slows to a much lower rate. Furthermore, if the straw is dried and then re-exposed to high humidity, the level of microflora growth remains at this low level of growth.

3.4.4 Mechanical properties of straw bales

The 'elastic' modulus of single straw bales is around 1 N/mm^2, around 20,000–30,000 times lower than that for normal strength concrete. The compressive resistance of straw is around 0.017 N/mm^2, around 2000–5000 times lower than for normal concrete.

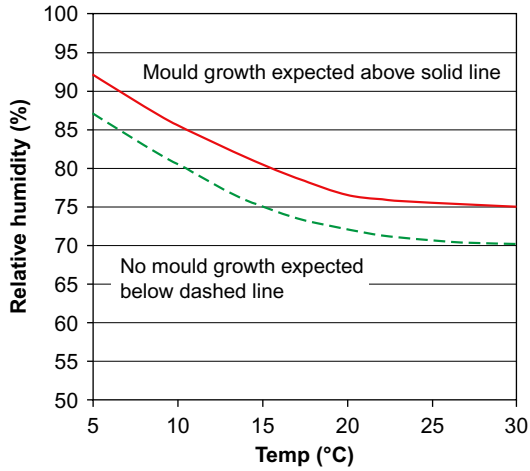


Fig. 3.18 Wheat straw isopleth (Sedlbauer *et al.*, 2011).

Therefore, rendered straw-bale construction derives its load resistance primarily from the relative strength and stiffness of the render coats, usually lime, cement-lime-based, rather than the much weaker straw (King, 1996; Vardy, 2009). However, in this composite behaviour, the straw bonded to the render provides important lateral restraint to the slender load-bearing coats. Unrendered straw can carry modest loads too, but generally, an alternative structural frame is provided (King, 2006; Vardy and MacDougall, 2012).

3.4.5 Acoustic properties of straw bale construction

The composite form of rendered straw-bale construction, combining a relatively dense and stiff outer surface with a lighter less dense and wide interior, provides good acoustic properties. Studies have confirmed that rendered straw-bale walls achieve sound reduction values around 43–55 dB (Goodhew *et al.*, 2010; Wall *et al.*, 2012).

3.4.6 Fire resistance of straw bale construction

Concerns about the fire resistance of straw-bale construction are commonly held. However, various tests on the fire resistance of rendered straw bale (Fig. 3.19) have generally shown that performance is comparable with many other forms of more conventional construction. In a lime-rendered wall test reported by Wall *et al.* (2012), the 30 mm render coats sustained full fire loading for around 90 min before failure, surpassing the 30 or 60 min ratings required for low-rise applications in the United Kingdom.

Fig. 3.19 Straw-bale panel after fire test.

3.4.7 Compressed straw board

Compressed strawboard is a manufactured wall panel product, developed over 70 years ago, that is formed by compacting and heat-bonding straw in a continuous extrusion process. The surfaces of the strawboard are usually sealed with building paper (similar to that found on gypsum boards). The density of compressed strawboard can vary between 150 and 600 kg/m^3, though it is most commonly produced between 280 and 470 kg/m^3 (board thickness 58 and 38 mm, respectively). Manufacturers include Stramit, Ekopanely, DURRA and COOBIO. Due to the extrusion process, the mechanical properties of compressed strawboard are orthogonal. Current applications for compressed strawboard include internal walls, partitions and linings, roofing and ceiling panels and door panels. In the United Kingdom, the specifications for compressed strawboard are covered by BS 4046 (1991).

3.4.8 Conclusion

Straw offers a sustainable supply of raw materials for construction, derived as a coproduct from essential food production. Supported by construction innovation, research and development, straw bale, including developments such as certified prefabricated panel construction, has supported its wider acceptance.

3.5 Bamboo and rattan

S. Knapic[*,†], *A. Bajraktari*[‡], *L. Nunes*[†,§]
*University of Lisbon, Lisbon, Portugal
†LNEC, Lisbon, Portugal
‡University of Applied Science in Ferizaj, Ferizaj, Republic of Kosovo
§cE3c/ABG and University of the Azores, Azores, Portugal

3.5.1 Introduction

Bamboo and rattan are widely known as the most important of the 'nontimber' forest products (*NTFP*) in Asia. The use of its fibres can be an interesting alternative to the traditional timber harvesting. Bamboo and rattan fibres are abundant, renewable, recyclable and biodegradable (Fig. 3.20) and though very similar in aspect have nevertheless some distinct characteristics.

Bamboo is an agricultural crop that belongs to the grass subfamily Bambusoideae (family Poaceae) comprising over 70 genera and 1200 species with an estimated annual production of 15–20 million tons of material (Fei *et al.*, 2016). It consists of cellulose fibre embedded in a lignin matrix (Seema Jain and Jindal, 1992; Lakkard and Patel, 1980). It is a composite material reinforced axially by fibres called vascular bundles.

Bamboo is one of the fastest growing plants in the world; it has low density, low cost, high mechanical strength, stiffness, high growth rate and ability to fix atmospheric carbon dioxide (Jindal, 1986; Ray *et al.*, 2004; Osorio *et al.*, 2010; Thwe, 2003). These properties enable it to be used as a construction material. However, it does have some disadvantages such as high moisture content, the difficulty of extracting fine and straight fibres and thermal degradation during manufacturing (Osorio *et al.*, 2010; Li *et al.*, 1994). The natural resistance of bamboo against insects and fungal attack is considered as low and has been regarded as a shortcoming for some applications (Liese, 1987). Particularly, the resistance against termites and wood-boring beetles deserved

Fig. 3.20 Bamboo (left) and rattan (right).

Fig. 3.21 Bamboo (left) and rattan (right) fibres.

some attention in recent years, and significant differences were found between bamboo species (Febrianto *et al.*, 2014).

Rattans are naturally renewable palms (Arecaceae, Calamoideae), superficially similar to bamboo and present solid stems. They are much easier to harvest, requiring simpler tools and are easier to transport.

Natural fibres like bamboo and rattan (Fig. 3.21) are emerging as cost-effective and apparently ecologically superior substitutes to glass fibres as reinforcement in composite materials (Zakikhani *et al.*, 2014).

It is expected that the products developed with these fibres not only are sustainable but also have low density, high dimensional stability, good processability and favourable mechanical properties (Abdul Khalil *et al.*, 2012; Bansal and Zoolagud, 2002; Chung and Yu, 2002; Habibi *et al.*, 2016; Hunter, 2003; Liese, 1996; Long *et al.*, 2015; Olorunnisola, 2005; Olorunnisola *et al.*, 2005a,b; Shang *et al.*, 2015; Van Der Lugt *et al.*, 2003).

3.5.2 Main characteristics and properties of developed products regarding their suitability for the building sector

The utilisation of bamboo fibres as a reinforcement in composite materials has increased in the recent years responding to the demand for developing biodegradable, sustainable and recyclable materials, and its mechanical properties are comparable with those of glass fibres (Osorio *et al.*, 2010; Khalil *et al.*, 2012; Zakikhani *et al.*, 2014) (Figs 3.22 and 3.23).

Traditionally, bamboo has been used in various living facilities and tools, which owes to its high strength and weight. This property is due to the longitudinal alignment of fibres. Bamboo has 60% cellulose with high content of lignin, and its microfibrillar angle is 2–10 degree. In practise, it is mandatory to fabricate the bamboo-based composites in addition to the extraction of bamboo fibres in a controlled way (Shin and Yipp, 1989; Okubo *et al.*, 2004). Its structural variation, mechanical properties, extraction of fibres, chemical modification and thermal properties had made it versatile for the use in composite industry (Amada *et al.*, 1997). Despite its finer mechanical properties, bamboo fibres are brittle when compared with other natural fibres, which is due to the extra lignin content.

Fig. 3.22 Examples of recent bamboo composites in building applications.

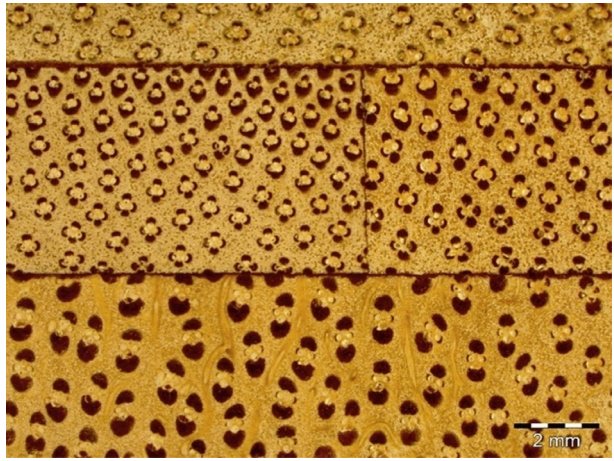


Fig. 3.23 Anatomical detail of a wood floorboard made with mixed species of bamboo.

As referred, it is difficult to extract fine and straight fibres. To overcome this, several studies have been done to classify and describe various procedures that have been developed to extract fibres from raw bamboo (Deshpande *et al.*, 2000; Das and Chakraborty, 2006a,b, 2008; Das *et al.*, 2006; Jain *et al.*, 1992, 1993; Zakikhani *et al.*, 2014). Results pointed to the fact that lignin has a major effect on the mechanical properties of the extracted fibres and that it is essential to control and reduce their moisture content. Extraction can be done mechanically (steam explosion method, retting, crushing, grinding and rolling mill) and chemically (degumming, alkali or acid retting and chemical retting) and combined mechanical and chemical extraction.

Degradation of bamboo mechanical properties with increasing moisture content was demonstrated in recent studies (Xu *et al.*, 2014); the values are significant below fibre saturation point and less pronounced at higher moisture levels.

A recent study on viscoelasticity damping behaviour of structural bamboo (Habibi *et al.*, 2016) revealed an important contribution to understand the intrinsic viscoelasticity in other biological materials with hierarchical structures and to optimise the design of bio-inspired composites with favourable structural properties.

Fei *et al.* (2016) studied the enhancement of the weatherability of bamboo-fibre-based outdoor building decoration materials using nano-TiO_2.

Another recent study on tensile properties of bamboo-fibre-reinforced polypropylene composites impregnated with calcium carbonate nanoparticles showed an increase of 16% on tensile strength, 22.2% on modulus of elasticity and 5.2% on elongation at break (Wang *et al.*, 2015). Shang *et al.* (2015) developed a new method for measuring properties of vascular bundles in moso bamboo (*Phyllostachys edulis*), recording values for tensile strength of 709.96 MPa and for modulus of elasticity (*MOE*) of 44.67 Gpa.

Bamboo bahareque walls were studied (González and Gutiérrez, 2005). These walls have a timber frame with split bamboo in the middle and are covered with cement plaster on both sides. Results show that these walls have enough capacity to withstand earthquake-induced loads of considerable magnitude, presenting some ductile behaviour under cyclic loading.

Several trials were done to produce bamboo particle board and medium-density fibreboard (*MDF*; Hiziroglu *et al.*, 2007; Lee *et al.*, 2006; Li *et al.*, 2004; Sumardi *et al.*, 2007). The use of bamboo as a (partial) wood substitute for manufacturing MDF panel production gives good perspectives. It was shown that partial substitution of spruce with bamboo did not affect the quality and properties of particle board and MDF panels (Van Acker *et al.*, 2000).

Several studies focus on the mechanical properties of bamboo. Ahmad and Kamke (2005) focused on its physical and mechanical properties. Low *et al.* (2006) addressed its microstructure, mechanical impact and fracture properties. Obataya *et al.* (2007) compared the bending properties of split bamboo culm with those of spruce and beech wood specimens. Verma *et al.* (2012) evaluated the tensile properties of bamboo laminae. Yu *et al.* (2014) measured the mechanical properties of single bamboo fibres to understand its potential as reinforcing material. Gutu (2013) evaluated the strength properties of bamboo, in order to resist different forces or load on structural members.

A study on the comparison of bending creep behaviour of bamboo/poplar plywood and bamboo-laminated veneer lumber showed an increase of values regarding density, modulus of rupture (*MOR*), MOE and load capacity of the latest (Ma *et al.*, 2014).

Similar to timbers, bamboo shows creep behaviour under sustained load. A study made on bamboo-poplar sandwich beams and nonreinforced poplar beam showed the long-term efficiency of bamboo laminae reinforcing low-quality wood beams and their subsequent creep behaviour (Amino, 2005).

Bamboo charcoal has been used as a reinforcing filler in wood-plastic composites (Li *et al.*, 2014a,b). Results showed that bamboo charcoal could have strong interfacial interaction with the composites, showing higher water resistance, flexural properties and tensile and thermal properties. The presence of bamboo charcoal resists the influence of water absorption on the composite's mechanical properties.

Rattan-cement composites were developed and their strength properties and potential uses studied (Olorunnisola, 2005). The results found this product to be suitable for applications in the production of insulation boards and bricks for bearing walls in low-rise buildings. Cement-rattan mixing ratio, rattan particle size and the interaction of both variables had significant effects on density (varying from 764 to 1340 kg/m^3), MOR (ranging from 0.8 to 5.2 N/mm^2) and modulus of elasticity (MOE ranging from 130.2 to 2830.7 N/mm^2).

Furthermore, a recent study on the mechanical characterisation of rattan fibre polyester composite (Rachchh *et al.*, 2014) analysed properties like tensile, flexural, density and hardness. The results pointed towards the improvement of the mechanical properties up to 12.5% of fibre level.

3.5.3 Conclusion

The concept of sustainable development linked with gradual exhaustion of resources has promoted the study and improvement of materials, which had a local tradition of use to larger and different applications. That is clearly the case of bamboo and rattan uses by the building sector.

This strategic resource combines rapidly renewable properties, enough strength, pleasant texture and cost-effectiveness—making it an ideal building material and a potential driver of sustainable development in many parts of the world.

3.6 Reed

J.M. Greef, C. Brischke*[†,‡]
*Institute of Crop and Soil Science, Braunschweig, Germany
[†]Leibniz University Hannover, Hannover, Germany
[‡]University of Göttingen, Göttingen, Germany

3.6.1 Reed as thatching material

Reed (*Phragmites australis* (Cav.) Trin. ex Steud.) is a traditional building material in many parts of the world. It is particularly used for thatching roofs, which is considered as a demanding crafts technique, and even today requires a lot of manual work

Fig. 3.24 Artwork made from reed
From H.S. Horling, Vakfederatie Rietdekkers, Nijkerk, The Netherlands.

and technical skills (Fig. 3.24). Reed is delivered and processed in bundles that are fixed to the battens of the roof structure forming up to 40 cm thick reed layer and giving the characteristic appearance of traditional housing in many European countries (Holzmann *et al.*, 2012). Regional differences in building techniques and design form characteristic types of thatched roofs that can be supplemented with additional specific materials for the ridge such as heather, straw or sea blite. Many historic thatched buildings remain even though the thatch requires maintenance and renewal in intervals of 50 years or even longer (e.g. Haslam, 1989).

3.6.2 Performance of reed

3.6.2.1 Premature decay in reed thatched roofs

During the last decades, a significant number of prematurely failing roof structures thatched with reed were reported (Haslam, 1989; Kirby and Rayner, 1989; Anthony, 1999; Püttmann, 2011). Various agents and changes in building practise came into consideration, causing service lives of thatched roofs of as little as 10 years or less. A lot of circumstances may contribute to this development. Moisture on roofs is one of the most important parameters that supports early deterioration (Haslam, 1989). In addition to construction characteristics of the roofing, changes in the quality of the material seem to have crucial effects on the moisture and the durability of the material (Brischke and Hanske, 2016; Hofmann *et al.*, 2016).

The water absorption of stems is determined by the morphological capillary structure in detail by diameter, wall thickness and length of the stems. Ingredients, that is, the content of lignin, have a function in the way to prevent water absorption in agglutinating vascular bundles. This process occurs during the drying process of stems after the harvest. Other ingredients, that is, hemicelluloses, could be of importance for microbiological activities if the stem material is wet (Dosdall *et al.*, 2014).

3.6.2.2 Composition of reed stem material

Fig. 3.25 shows the distribution of lignin and hemicellulose content along a gradient from the bottom to the top of the stem. The lignin content is highest in the bottom and decreases within the first centimetres of the stem. In contrast, the hemicellulose content increases constantly along the stem. High lignin content leads to high resistance against mechanical impact of the stem across the water line of the lake/river shore. Above this line, lignin is less necessary and decreased with stem height. This gradient reflects the importance of the reed stubble in view of a resistant material. It is anticipated that stem material with high lignin content in the basal section of the stem will prevent water uptake. In the upper parts of the stem, degradable cellulose material is increased instead of lignin. Enhanced microbiological decomposition could be forced.

3.6.2.3 Water absorption and decomposition of reed material

Samples of reed stems were analysed across the gradient of bottom, middle and top section. The water absorption was measured using small reed cylinders/bundles (5 cm length and 45 mm diameter in cross section) over a period of 24 h. The specific weight decreases as shown in Table 3.2 from the bottom to the top of the stem. This gradient shows that the material of the bottom is much more compacted than the middle and top sections. It reflects the resistance of the stubble.

The water absorption in terms of the absorption rate and absorption expressed in percentage of volume increases along a gradient from the basal section to the upper section.

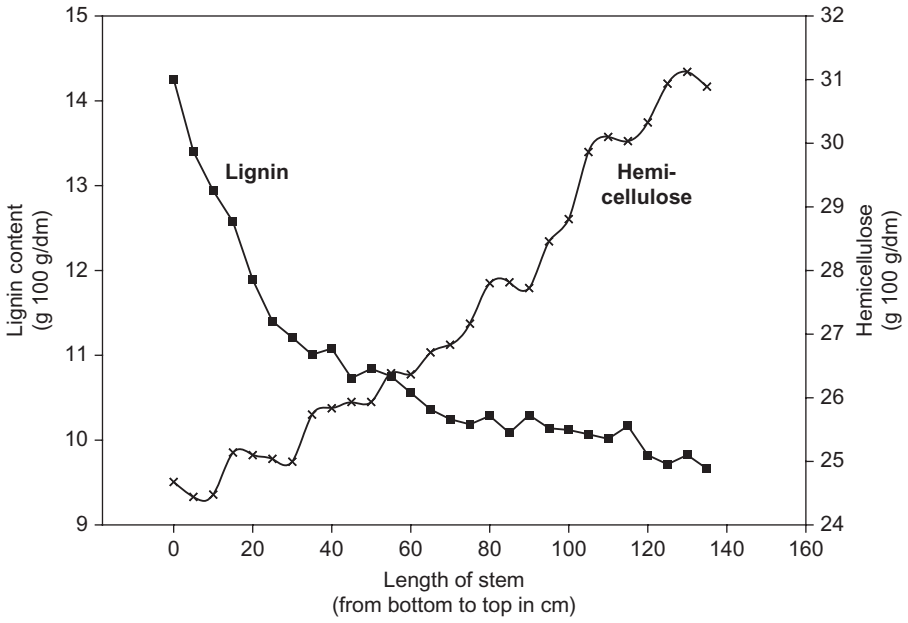


Fig. 3.25 Content of lignin (squares) and hemicelluloses (crosses) from the bottom up to the top of a reed stem.

Table 3.2 Specific weight, water absorption and in vitro digestibility of reed samples (reed bundles of 5 cm length and 45 mm diameter each section)

Section of stem	Bottom (0–5 cm)	Middle (50–55 cm)	Top (100–105 cm)
Specific weight (g/cm^3)	0.24	0.20	0.18
Water absorption coefficient (L/m^2/h$^{0.5}$)	1.58	2.28	2.55
Water absorption (vol% in 24 h)	4.28	6.32	7.15
In vitro digestibility (%)	13.56	14.02	15.27

This would affect the moisture content of the stem material. According to an enzymatic procedure with incubation in acid pepsin and enzymatic method (enzymatic soluble organic matter (*ELOS*); Anonymous, 1997), the stem material in vitro digestibility was determined. The result shows clearly the increase of decomposition in dependence of the decreased content of lignin and increased content of hemicellulose. This result means that the stubble of the reed stem is not as degradable as the middle and upper parts of the stem. However, the middle and upper sections are more at risk to microbiological degradation.

3.6.2.4 Water absorption of different origins of reed

An evaluation of different origins of reed sampled from China, Europe and Turkey shows a wide range of quality parameters (Wöhler *et al.*, 2016). Different origins of reed were investigated using small reed bundles (of 5 cm length and 45 mm diameter each section) of the basal and middle part of a reed stem. Fig. 3.26 demonstrates the interaction of lignin content and reed origins (digits in the figure indicate a reed origin) in dependence of the stem section (basal/middle). A very low absorption in the basal section is found for the origin (48, solid arrow). Concurrently, the middle section shows a low uptake. In contrast, the origin (45, dashed arrow) has a higher water absorption in the basal and the middle section. The uptake in the basal section is as high as other origins in the middle part. It is assumed that in the origin 45 the stubble does not exist. Possibly, the stubble is removed by changed harvest technique. The cutting edge of a modern harvester is higher compared with mowing by traditional hand techniques or small harvester. The removal of the stubble cuts of the section with the high level of lignin. High water absorption consequently leads to a higher moisture content, which endangered microbiological degradation in the stem material.

3.6.3 Conclusions

Lignin decreases and hemicelluloses increases from the bottom to the top along the reed stem. High lignin content prevents the uptake of water, whilst high hemicelluloses content forces microbiological degradation. To provide a good quality of reed thatching material, removal of the stubble should be avoided. Subsequently, the reed crop stock should be harvested as close to the ground as possible. With the loss of the stubble, the impact of increased water absorption and a following microbiological

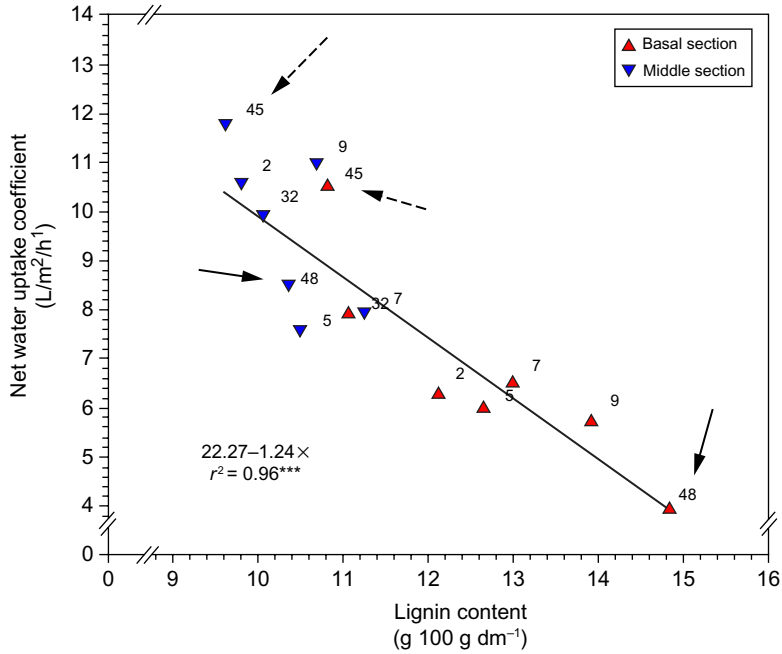


Fig. 3.26 Regression between content of lignin (squares) and water absorption rate from basal (upright triangle) and middle (downward triangle) section of reed stem (the digits indicate different reed origins: solid arrow shows origin 48 and dashed arrow shows origin 45). ***P < 0.001.

degradation is jeopardised. The evaluation of several reed samples gives evidence that the quality in view of 'high-lignin-level stubble' is quite different depending on origin. This may indicate that the practise of harvesting and cutting procedures is not uniform, resulting in a wide range of material quality for thatching.

3.7 Wool

E. Mansour, G.A. Ormondroyd*[*,†]
*Bangor University, Bangor, United Kingdom
[†]University of Bath, Bath, United Kingdom

3.7.1 Introduction to wool fibre

3.7.1.1 Structure and composition

The main fibre

Sheep's wool and other animal wool/hair are known to be composed of about 90% by weight cortical cells, surrounded by about 10% flat cuticular cells aligned in a scalelike fashion as shown in Fig. 3.27 (Bonès and Sikorski, 1967; Bradbury and

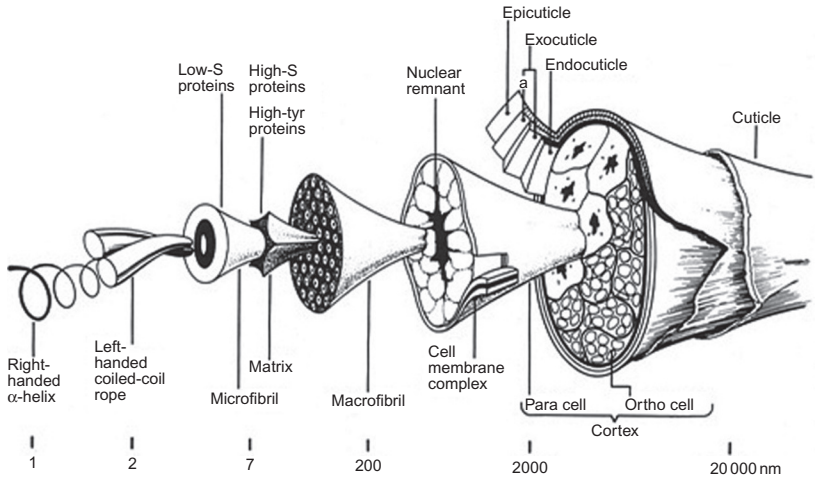


Fig. 3.27 Wool fibre structure showing cortical and cuticular parts (CSIRO, 2011).

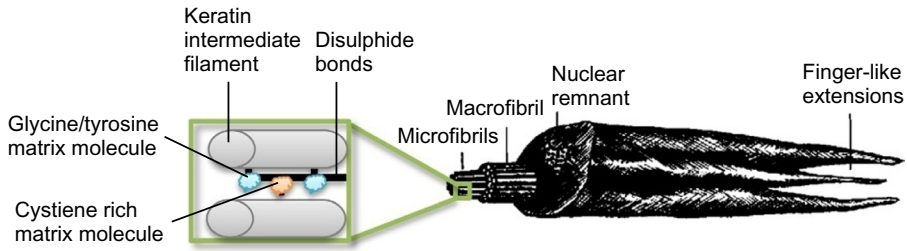


Fig. 3.28 Shape of an individual cortical cell (Rogers, 1959).

Chapman, 1964; Rogers, 1959). Individual cortical and cuticular cells have a shape as shown in Fig. 3.28, where the fingerlike extensions interlock with the extensions of another cell (Rogers and Bawden, 2008).

Making up the core of the fibre, cortical cells contain several keratin intermediate filaments. Keratin is a tough fibrous protein that maintains its rigid structure via disulphide bridges, characteristic of the amino acid cystine, in addition to intra- and intermolecular hydrogen bonds. The keratin intermediate fibres collect together by a matrix that is composed of nonfibrous keratin-associated proteins and is either of a high glycine/tyrosine type or a high-sulphur type (i.e. rich in cystine). These fibres are complex and very little is known about them other than they are composed of two different types of proteins that are not similar in their amino acid sequence but are similar in their secondary structure. They are stabilised by α-helix hydrogen bonds and disulphide bonds, the latter being the bond that cements them to the surrounding matrix (Rogers and Bawden, 2008). They group into what is termed microfibrils, which in turn group into what is termed macrofibrils.

There are two types of cortical cells: ortho and para. Paracortical cells have a more uniform/fused keratin structure and are more resistant to chemical and mechanical attack, such as swelling, than the orthocortex (Bradbury, 1974; Kulkarni and Bradbury, 1974), which explains why wool fibre crimps. Different wool types vary in their fineness, which is attributed to this difference between cortical cells; finer wool fibres have two distinct halves of ortho- and paracortical cells (i.e. bilaterally distributed; see Fig. 3.27) that, when exposed to moisture, swell to different degrees and make the fibre bend. This crimp is what traps air pockets in between the fibres and gives wool its insulation properties.

The whole bundle of macrofibrils is encapsulated by the cuticle, which unlike the cortex is amorphous, but is composed of cells of similar interlocking extensions as the cortex. The outermost membrane on the fibre is the epicuticle, about 13 nm thick (Swift and Smith, 2001) and resistant to chemical attack, with 12% of its protein component being keratin (Negri *et al.*, 1993; Ward *et al.*, 1993). The epicuticle is highly insoluble due to isodipeptide cross links of 1-amino-(g-glutamyl)-lysine (Folk, 1977). It is longitudinally striated with ridges about 350 nm long, which face away from the root; this helps dirt and water droplets to drop away in one direction. The striation is what gives wool fibres a great frictional force and allows felting.

Below the epicuticle is the dense A-layer, 35% of it being cystine (Negri *et al.*, 1993). This layer is the start of the underlying exocuticle (Bradbury and Chapman, 1964), which is stabilised by disulphide bonds of keratin. The exocuticle contains high-sulphur keratin-associated proteins that are related to the matrix proteins (Rogers and Bawden, 2008). In contrast, the layer below that, the endocuticle, does not contain keratin. In between cuticle and cortical cells is a cell membrane complex, which in turn is divided into β- and δ-layers. However, the cell membrane complex of the cuticle behaves differently than that of the cortex, the former containing citrulline and being resistant to modification with formic acid (Peters and Bradbury, 1976). An illustration of the layers of cuticle cells and an image showing the cell membrane complex in cortical cells are shown in Fig. 3.29.

Through ultrasonic disruption of wool fibres, the different components of a wool fibre can be separated and studied, as performed by Bradbury (1974). Table 3.3 summarises the morphological composition of Marino wool. Small and perhaps insignificant differences in amino acid composition can be seen between different wool types, although statistically significant differences are noted when it comes to their elemental content (Patkowska-Sokola *et al.*, 2009). However, large differences are observed between the cuticle and cortex compositions of the same wool type (Bradbury *et al.*, 1965). The authors made the conclusion that all amino acids abundant in the cuticle are classed as non-α-helix-forming and the rest except for two that are scarce in the cuticle are classed as α-helix-forming and three amino acids that are not classified (Blout and Stahman, 1962). This explains the reason why the cuticle is amorphous and less polar than the α-helical cortex. Differences in amino acid content between ortho- and paracortical cells are too small to contribute to their differing behaviour with water and stress (Chapman and Bradbury, 1968).

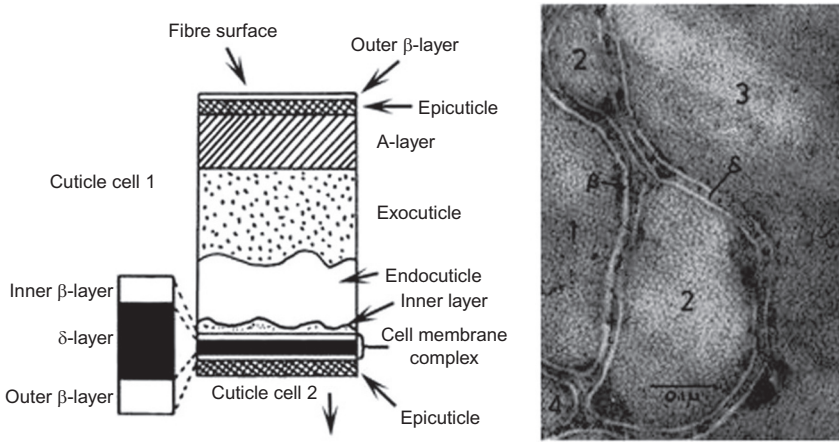


Fig. 3.29 Left—a near-surface transverse diagram of a fibre (Swift and Smith, 2001). Right—electron micrograph of the cortex of Lincoln wool showing a cross section of the cells separated by darkly coloured δ-layer, which is sandwiched between lightly coloured β-layers (Peters and Bradbury, 1976).

Table 3.3 Morphological composition of Merino wool (Bradbury, 1974)

Component		Percentage of whole fibre
Cuticle	Epicuticle[a]	0.1
	Exocuticle	6.4
	Endocuticle	3.6
Cell membrane complex	Lipid	0.8
	Soluble protein	1.0
	Resistant membranes	1.5
Cortex	Nuclear remnants and intermacrofibrillar material	12.6
	Microfibrils[b]	35.6
	Matrix[b]	38.5

[a] Approximate.
[b] Ratio of microfibrils to matrix is that of Lincoln wool.

The surrounding lipid layer

In the case of unmodified and undamaged wool, the fibre is covered by a layer of lipids that is about 0.9 nm thick that comprises a quarter of the epicuticle (Negri *et al.*, 1993). These lipids, which are mainly 18-methyleicosanoic acid (*18-MEA*), are covalently bonded to the keratin protein (Evans *et al.*, 1985). Swift and Smith (2001) hypothesise that the lipid layer is disordered (Fig. 3.30C) and dynamic, changing its position when

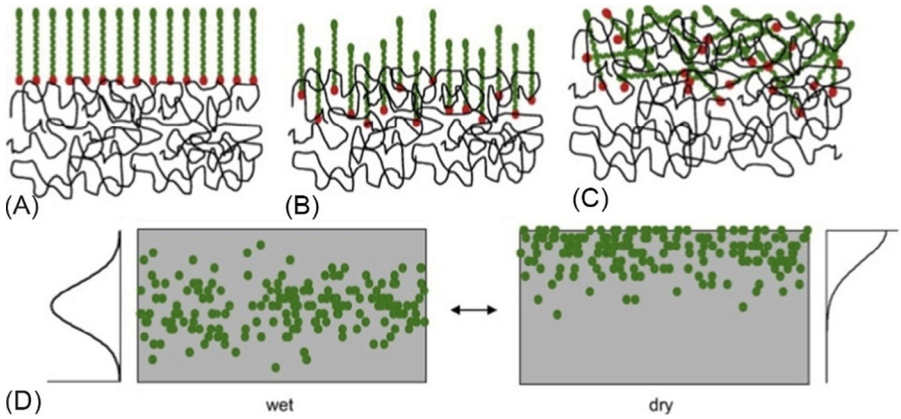


Fig. 3.30 Representations of the arrangement of the lipid layer shown in green and underlying protein layer shown in black. (A) Homogenous layer. (B) Slightly disordered layer. (C) Disordered layer. (D) Dynamic change of the position of the lipids (green dots) in the protein matrix (grey) in response to the surrounding environment.

the surrounding environment changes from wet to dry (Fig. 3.30D); when placed in a hydrophobic environment, the hydrophobic chains of the lipid layer face outwards but reorient itself upon exposure to an aqueous environment so that the protein (amide) and polar side-chain groups of the proteolipid are oriented outwards (Maxwell and Huson, 2005).

These lipids can be removed by potassium *tert*-butoxide in *tert*-butanol or methanolic potassium hydroxide solutions (Ward *et al.*, 1993), as 5 min of treatment oxidises the surface cysteine, thus decreasing the fatty acid content by about half and significantly increasing wettability and friction. Therefore, similar treatments used in the scouring process get rid of most of this layer. These lipids are not to be confused with lanolin, which are unattached sterols, sterol esters and other lipids secreted by sebaceous glands that coat wool fibres as they grow (Schlossman and McCarthy, 1978). However, there are claims that the fibre's layer cannot be physically or chemically removed uniformly and without damaging the underlying protein, suggesting that it is an integral part of the structure (Maxwell and Huson, 2005). On the other hand, Swift and Smith (2001) observed with no alteration to the visual appearance of the surface of the fibres as viewed by scanning electron microscopy (*SEM*) and scanning probe microscopy (*SPM*) after successive treatments but agreed that the removal is 'patchy'. That being said, the surface structure of wool is complex, and the chemical functionalities are not all understood.

Microscopic properties

A past study on the elasticity of wool in various organic solvents concluded that the size of the capillaries in dry English Cotswold wool is more or less equal to the size of *n*-propanol (Speakman, 1931). The internal surface was calculated to be approximately

1×10^6 cm^2/g and the maximum moisture absorbed to be about 20% of its weight. In water, the fibres swell, increasing the capillary size from 0.6 to 4.1 nm, which corresponds to an increase in the force required to stretch the fibre. It has also been shown that some organic liquids that are too bulky to enter the capillaries on their own may gain access and modify the chemical and physical properties of the fibre when water is added. Short-chain acids (formic and acetic) showed a reversible collapse of the capillaries, increasing diameters by 40%–50%; the physical properties were restored by simply washing with water.

3.7.1.2 Wool as a construction material

In the construction industry, wool fibres' use is mainly restricted for thermal and acoustic insulation. Literature describes natural-fibre-based composites to be superior from a life-cycle assessment (*LCA*) point of view to glass-fibre-reinforced composites for four main reasons: lower environmental impact, reduction of the amount of more polluting base polymers, contribution to transportation efficiency due to their lighter weight and contribution to energy and carbon credit by end-of-life incineration (Joshi *et al.*, 2004). The drive to deviate from traditional insulation material can be summed up by the associated problems listed in Fig. 3.31 (Desarnaulds *et al.*, 2005). Many life-cycle inventories have been set up to compare environmental and social impacts of insulation material: Ecoinvent in Switzerland (Ecoinvent [WWW Document], 2016), BRE Eco-profiles in the United Kingdom (BRE Group: Green Guide to Specification [WWW Document], 2016) and Eco-indicator '99 in the Netherlands (PRé Sustainability [WWW Document], 2016) to name a few. As part of the said interests and studies, wool-based insulation has been investigated.

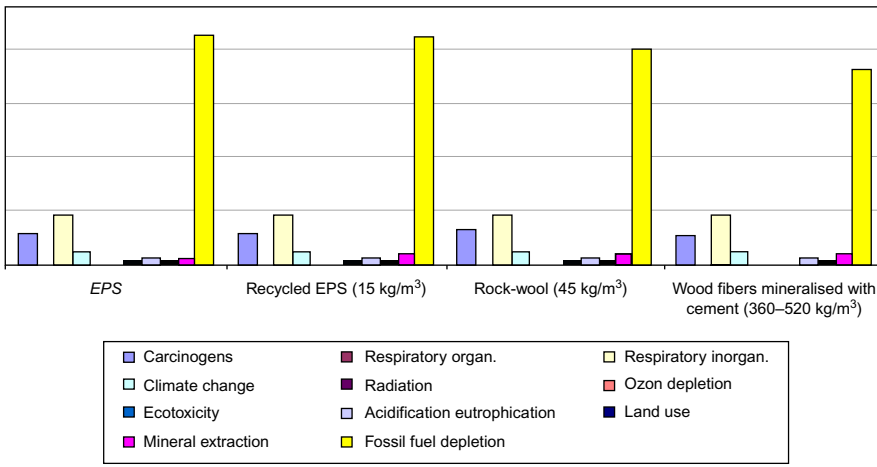


Fig. 3.31 Evaluation of traditional insulation materials with regard to related issues of concern, as per Eco-indicator '99 (Desarnaulds *et al.*, 2005).

How wool based insulation compares

As all insulation products go, the objective of using wool-based insulation by the construction industry is multifold (Al-Homoud, 2005), with its largest advantages lying in thermal attributes comparable with most inorganic and organic insulation (Papadopoulos, 2005), vapour condensation prevention (Li *et al.*, 1992; Tuzcu, 2007) and reduced energy costs through its use. In fact, thermal insulation from sheep wool has comparable characteristics with mineral/rock wool and in some applications even performs better (Zach *et al.*, 2012).

The ecological factors of construction material are also highly important, ranging from production energy usage and resultant pollution to installation and use (Berge, 2007). Wool-based insulation is shown in Fig. 3.32 to have a very mild nonrenewable energy fraction and a negative global warming potential, surpassing

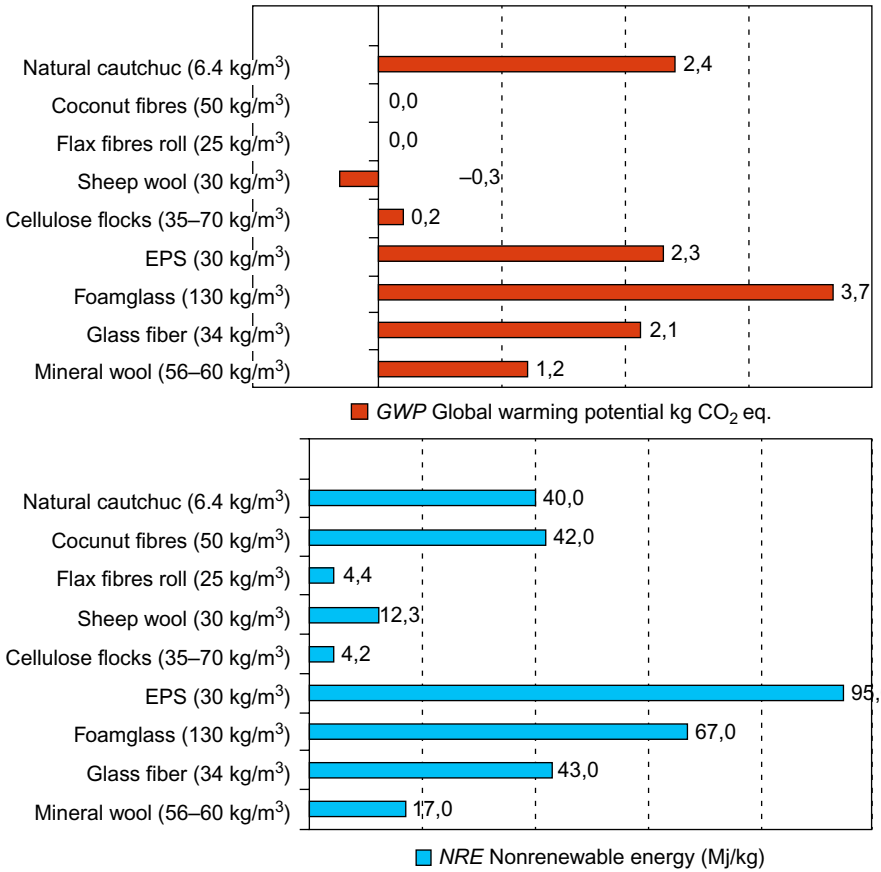


Fig. 3.32 Global warming potential and nonrenewable energy fraction related to insulation products based on different materials, based on the Ecoinvent database (Ecoinvent [WWW Document], 2016; Asdrubali, 2006).

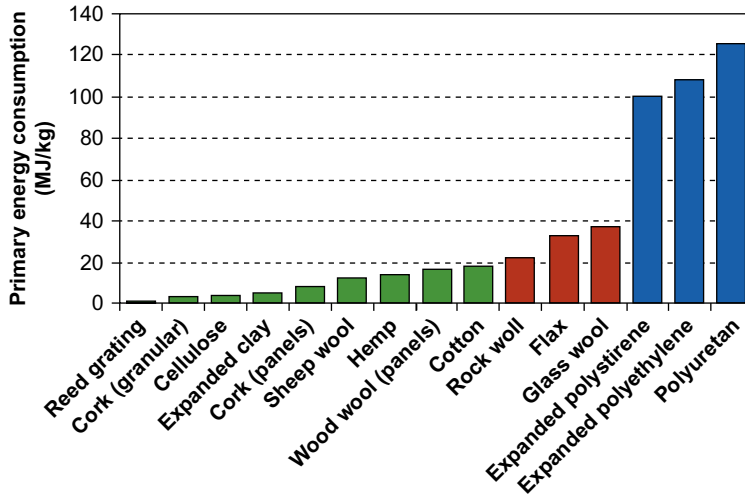


Fig. 3.33 Estimated primary energy required for different insulating materials (Asdrubali, 2006).

other natural-based insulations that have no contribution to global warming potential (Desarnaulds *et al.*, 2005). Fig. 3.33 lists the estimated primary energy required for the extraction, transport, production and packing of different insulating materials, showing wool insulation as significantly less energy intensive in that regard (Secchi, 2005). Patnaik *et al.* (2015) state that wool-fibre-based materials consume lowest amount of energy during material use and disposal stage than any other existing natural materials.

When compared with ease of installation, wool is known to be nonirritating and highly flexible. Another advantage is end of life; incineration for energy is always an option, and a composability test as per ASTM D6400 standard performed on wool-based insulation showed biodegradation of 80%–85% in 50 days, which is higher than that of microcrystalline cellulose powder (Patnaik *et al.*, 2015).

Practical downsides of the use of wool fibres compared with most conventional insulation products include the need to use additives for moth control and in most cases fire retardancy, although it exhibits low flammability characteristics (Mortan and Hearle, 1975).

Health concerns have been raised throughout history with regard to the processing of wool (Mansour *et al.*, 2014), specifically in terms of inhalation of dust particles. But as long as precautions such as scouring (i.e. cleaning) the wool preprocessing and applying treatments in a controlled manner, related microbial and chemical inhalation risks can be eliminated. Explosion risks are also associated with wool dust, as with any organic dust, but can be minimised by simple good housekeeping in production facilities. That being said, risks associated with processing fibrous insulation material are restricted to factory sites when it comes to wool insulation but are wider and still

prevalent when it comes to synthetic fibrous insulation as their dust exposure extends more so to installers than it does to production operatives (Marchant *et al.*, 2002).

Further comparisons are highlighted in Table 3.4. The push for improvement does not lie primarily under the enhancement of thermal resistance but only minorly on that accompanied with improvements in the other areas discussed (Papadopoulos, 2005).

3.7.2 Thermal performance

Thermal conductivity (*k*-values) is the main measurement of how well thermal insulation performs. Obtained values in studies differ—mostly between 0.03 and 0.04 W/mK—depending on several factors such as wool types used (which is mostly not stated), test conditions and most importantly sample density. The higher the bulk density of the sample, the more restricted the air flow between the fibres is, leading to less convection and therefore lower thermal conductivity values (Zach *et al.*, 2012).

Wool-based insulation products have been assessed in a variety of forms and combinations with the focus being mainly on what is termed 'waste wool', that is, wools that are low cost and not used by the textile industry. The drive of such studies is to shed light on more sustainable and reasonably economic substitution for conventional insulation products. One such study compared nonwoven mats composed of two types of wool, coring wool and dorper wool, along with a combination of each wool with recycled polyester fibres, each comprising half the thickness of the mat (Patnaik *et al.*, 2015). With regard to thermal properties, the mats were measured at k-values around 0.030–0.034 W/mK, largely depending on the temperatures they were tested at. Although mats composed of wool only were shown to insulate better than mats composed of recycled polyester fibres only, mats composed of a combination of wool and recycled polyester showed no significant difference compared with mats composed of wool, highlighting a possibility of using complex composites containing wool fibre to reinforce thermal insulation. The trend with insulation materials shows an increase in thermal conductivity as the temperatures they are tested at increase (Abdou and Budaiwi, 2013).

3.7.3 Acoustic performance

Acoustic insulation has more than one phenomenon behind it (Patnaik *et al.*, 2015); sound waves can be absorbed, reflected and/or transmitted, with absorption being the main contributing factor to insulation. Sound absorption is dependent on the thickness of the material since waves convert their kinetic energy to low-level heat energy as it passes through particles due to friction; the more particles the wave passes through, the more dampened it becomes. However, another factor of importance is the ratio of the length of interconnected open pores to the material thickness, which is termed tortuosity. In higher thickness samples, sound waves have more path lengths of interconnected pores available to pass through, which causes frictional loss and better acoustic insulation.

Many acoustic solutions are reported in the literature based on sustainable material, ranging from fibrous material (D'Alessandro *et al.*, 2005) and waste rubber (Cheng

Table 3.4 Ranking of different insulation materials based on the properties of average, commercially available materials (Papadopoulos, 2005)

	Inorganic fibrous		Organic foamy			Organic fibrous				Inorganic foamy		Others		
	Glass wool	**Stone wool**	**EPS**	***XPS***	***PU***	**Sheep wool**	**Cotton wool**	**Cellulose**	**Coconut fibres**	**Perlite**	**Foam glass**	**Gypsum foam**	**Experimental cork**	**Wood wool**
Thermal attributes	○	○	○	○	+	○	○	○	○	−	○	○	○	−
Moisture resistance	○/+	○/+	○	+	+	○	○	○	○	+	+	○	○	−
Pressure resistance	−	○/+	+	+	+	−	−	−	−	−	+	−/○	+	+
Tensile resistance	+	+	○/+	○	○/+	+	+	○	○	○	−/○	○	○/+	−/○
Sound proofing	+	+	○	−/○	−/○	+	+	+	○/+	○/+	−/○	○	○	○/+
Reaction to fire	+	+	○	○	−/○	○	○	○	○	+	+	○	○	○
Resistance at biological dangers (insects, fungus, etc.)	+	+	+	+	+	○	○	○	○	+	+	+	○	+
Emissions during production	○/−	○/−	+	+	+	○/+	○/+	○/−	○	−/○	+	○/+	+	+/○
Cost for $k = 0.2\,W/m\,K$ achievement	+	+	+	−	○	−	−	○	−	−	−	−	−	−

(Continued)

Table 3.4 Continued

	Inorganic fibrous		Organic foamy			Organic fibrous				Inorganic foamy		Others		
	Glass wool	**Stone wool**	**EPS**	***XPS***	***PU***	**Sheep wool**	**Cotton wool**	**Cellulose**	**Coconut fibres**	**Perlite**	**Foam glass**	**Gypsum foam**	**Experimental cork**	**Wood wool**
Maximal exposure rates during production, handling and construction	○	○	+	+	+	+	+	+	○	+	+	+	+	+
Biopersistence of fibres	○	○	NA	NA	NA	+	+	+	+	NA	NA	NA	NA	NA
Use of CFCs, HCFCs and CO_2	NA	NA	−/○	−/○	−/○	NA	NA	NA	NA	○/+	+	+	+	NA
Toxicity in case of fire	NA	NA	○	○	−	+	+	+	+	+	+	+	○/+	NA
Embodied energy	+	+	○	○	○	○/+	○/+	○/+	○/+	○	○/+	○/+	○/+	○
Use of raw resources	+	+	−	−	−	+	+	+	+	+	+	+	○/+	○/+
Waste disposal	+	+	○	○	−	+	+	+	+	+	+	+	+	+
Reuse and recycle	○	○	+	+	−					○	○			○

(+), Good; (○), average; (−), poor; *EPS*, expanded polystyrene; *XPS*, extruded polystyrene; *PU*, polyurethane.

et al., 2003) to calabash residue (Pizzutti *et al.*, 2005) and shoe production residue (Hax *et al.*, 2000). It is reported that natural materials in general, including wool, show good absorbing performances, only generally being less efficient than conventional materials at 500 Hz (Asdrubali, 2006). For a double-leaf wall, wool insulation was shown to be equal or better at sound insulation than mineral wool of the same thickness (Desarnaulds *et al.*, 2005).

Sound absorption can differ depending on the wool type used in the insulation product. For example, nonwoven mats made out of dorper wool showed higher absorption coefficients α when compared with mats made out of the shorter-in-length coring wool fibres across the range of 50–5700 Hz, although the standard deviations overlap most of the values (Patnaik *et al.*, 2015).

3.7.4 Indoor air quality performance

3.7.4.1 Hygric performance

Natural materials are known to have a moisture buffering effect indoors. That is an important factor to consider (Korjenic and Bednar, 2011, 2012) since it causes occupants to be less susceptible to large changes of indoor relative humidities (Korjenic *et al.*, 2010). Due to their high porosity, wool fibres absorb moisture in an exothermic process (Stuart *et al.*, 1989) and release it when the surrounding relative humidity is low (Zach *et al.*, 2012).

No significant effect is observed on acoustic properties when wool-based insulation mats are exposed to high relative humidities; thermal conductivity, however, is heightened (Patnaik *et al.*, 2015). This decline in thermal resistance is dependent on the amount of moisture the fibres absorb, a common feature of insulation in general (Abdou and Budaiwi, 2013; Korjenic *et al.*, 2011); the most significant change occurs when the fibres absorb over 20% of their own weight in water, as seen in Fig. 3.34.

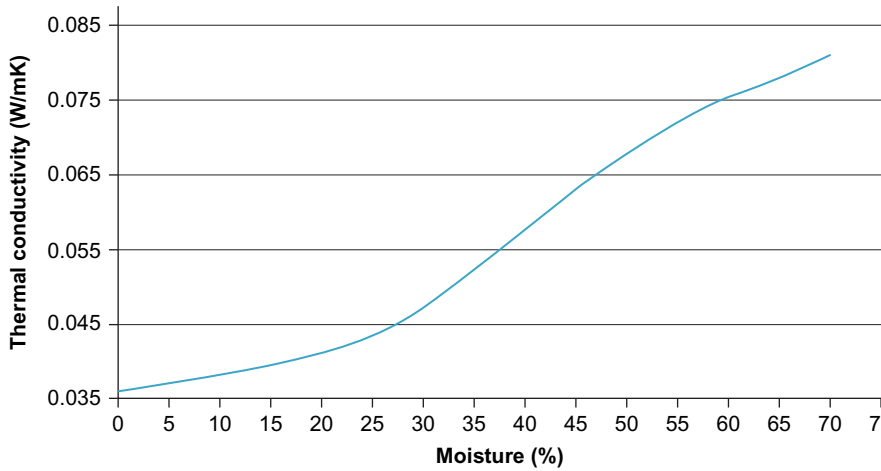


Fig. 3.34 Thermal conductivity of wool insulation as a function of the samples' moisture content (Zach *et al.*, 2012).

Cellulose flakes as another example show an increase of 0.5% in thermal conductivity for every 1% increase in moisture content, assuming that the relationship between the two is linear (Kehrer *et al.*, 2003). One study concludes that, since wool absorbs about 20% of their own weight in water under relative humidities between 30% and 60% RH at 23°C, its thermal performance would be affected only to a minor extent within that range (Zach *et al.*, 2012).

3.7.4.2 Volatile organic compound abatement

Indoor air quality (*IAQ*) has intrigued scientists since the mid-1800s (von Pettenkofer, 1858) and continued in the 1930s and 1940s, when the main concern was the spread of microbial agents within dwellings and public buildings (Shurtleff, 1933; Wells, 1943). Historical developments such as the London smog of 1952 instigated substantial air-pollution investigations, and differences in the health of people working indoors and outdoors were explored (Fairbairn and Reid, 1958). There has been a mild interest in the capacity of construction materials to contribute to a better atmospheric environment (Braun and Wilson, 1970); but the main studies investigating volatile organic compounds (*VOCs*) in buildings didn't start until relatively recently, with at least 50 studies conducted between 1978 and 1990 (Brown *et al.*, 1994). Unfortunately, indoor air pollution remains a recognised socio-economic problem (EEA, 2013; Franchi *et al.*, 2006), potentially causing the loss of a projected $10–$20 billion annually of projected savings, and productivity gains in the United States alone (Fisk and Rosenfeld, 1997). Based on further scientific findings, the World Health Organisation (*WHO*) compiled a set of statements emphasising the right to breathe healthy indoor air and the obligations of responsible authorities (WHO, 2000).

Formaldehyde, as one of the very VOCs, is of importance for three main reasons: Many building products emit it at significant rates (Meyer and Boehme, 1997); it is a gas in its natural state, so occupants are easily exposed to it; and some studies suggest that it has possible adverse health effects at certain concentrations (EPA, 1991; Nielsen and Wolkoff, 2010). It has been classified as a category 1B carcinogen, which is a classification largely based on animal evidence and presumes to have carcinogenic potential for humans (European Parliament, 2008).

Wool fibre is known to manage the problem when used as furniture, clothing or insulation (Seo *et al.*, 2009). Compared with previous studies, Curling *et al.* (2012) proposed a quick and simple method to quantify gaseous formaldehyde absorption by sheep wool: they exposed wool to formaldehyde gas whilst observing its weight change using dynamic vapour sorption (*DVS*). The 4.9% gain in weight shows that wool absorbs this quantity of formaldehyde from the surrounding air. The sample is then placed in a formaldehyde-free environment for several cycles of low to high relative humidity, allowing it to desorb the formaldehyde it contains. Interestingly, the weight of the wool sample does not drop down to its original weight but to 102.9% of its original weight. This quantity of formaldehyde is permanently bound to the wool structure.

Another study in this regard quantified the amounts of VOC absorbed by different wool types (Mansour *et al.*, 2016). Wool is shown to be able to absorb formaldehyde via DVS and limonene and dodecane via thermal desorption; the amounts absorbed

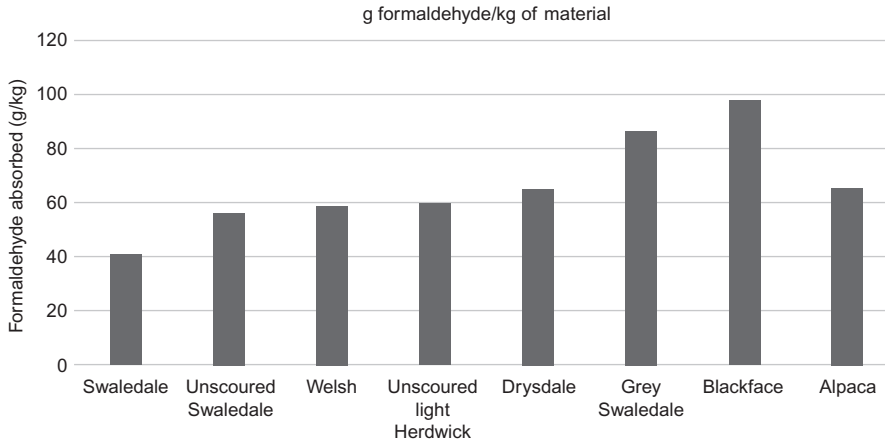


Fig. 3.35 Maximum amount of gaseous formaldehyde absorbed by different wool types post multiple exposure cycles.

vary somewhat depending on the wool type (Fig. 3.35 and Table 3.5), suggesting the possibility of customising wool-based insulation to absorb a certain range of VOCs that contaminate a certain building.

3.7.5 Conclusions

Wool fibres are the only proteinaceous material used in modern construction. Its properties as an insulation material stem from its complex microscopic and atomic structure. In comparison with conventional insulation material, wool-based insulation products are reported to be more sustainable in the true sense of the word from a whole life-cycle point of view and equally insulating in a thermal and acoustic sense. Certain downsides do exist: certain health risks associated with production that may arise if not managed properly, requirement of some additives and pretreatments, reduction in thermal performance with increasing relative humidity levels and lower sound absorption at 500 Hz.

However, one aspect where the use of wool-based insulation excels has to do with IAQ. Its moisture buffering ability softens shifts in relative humidity levels indoors, and a topic of recent research shows wool's potential at abating indoor VOCs.

Table 3.5 Percentage of used mass of toluene, limonene and dodecane absorbed by different wool types from a continuous gaseous flow

Sample	Toluene absorbed (%)	Limonene absorbed (%)	Dodecane absorbed (%)
Swaledale	0.00	31.66 ± 11.35	85.31 ± 7.29
Light Herdwick	0.00	39.99 ± 4.20	93.25 ± 7.92
Blackface	0.00	18.52 ± 5.67	67.77 ± 7.92
Unscoured Swaledale	18.87 ± 9.78	99.50 ± 0.76	99.50 ± 4.92

3.8 Peat

T. Teppand
Estonian University of Life Sciences, Tartu, Estonia

3.8.1 Introduction

Peat is a natural resource and may be considered as a semirenewable material in northern countries even if the *EU* does not accept this, because of perceived loss of wetlands during the 20th century. The future depends on sustainable use of this resource. There are two types of peat depending on the formation and application field. One type is older (nutrition from groundwater), well-decayed swamp peat, which is mostly used as a heating material and less as fertiliser, for gardening or in the pharmacy (Teppand, 2015), cosmetics and medical treatment since humic agents present are effective against bursal diseases (Orru *et al.*, 2007). The other, used in the agriculture as litter in cattle breeding, is little decayed pocosin or bog peat and is younger (nutrition from freshet) (Teppand, 2015). This type of peat has been widely used as an insulating material historically for log and frame houses and even as a structural material (in Iceland until 20th century), though such practises have fallen out of favour, mainly due to the labour-intensive processes involved.

The good physical and chemical properties of peat still make this a material of interest within the construction sector, and there is growing interest in commercial applications.

One ongoing study by the Estonian University of Life Sciences aims to

(a) collect the data regarding peat use and its application in building structures in the past
(b) find out or collect know-how of new technologies on how to better use peat, focusing on structural engineering and ecological methods

3.8.2 Distribution of mires and peatland

3.8.2.1 Global perspective

Globally, the mires and peatlands cover about 4 million km^2 (about 3% of whole landmass), containing 500 billion tons of carbon (WEC, 2016); however, those of commercial interest are mostly situated in the northern hemisphere, typically in areas where the use of peat has been predominantly as a heating source (Fig. 3.36). Peat is classified as nonrenewable resource because of environmental regulations laid out by the UN and EU. It means that using it mostly for getting energy is not deemed sustainable anymore, though this is not the case for energy-effective products, such as insulation materials.

The biggest deposits of peatlands by countries in the world are situated within the territories of Russia, Canada, Indonesia and United States (WEC, 2016).

The main producers and users of peat are Finland, Belarus, Estonia, Ireland, Indonesia, Sweden and the Russian Federation (WEC, 2016), though this is mostly still for heating purposes.

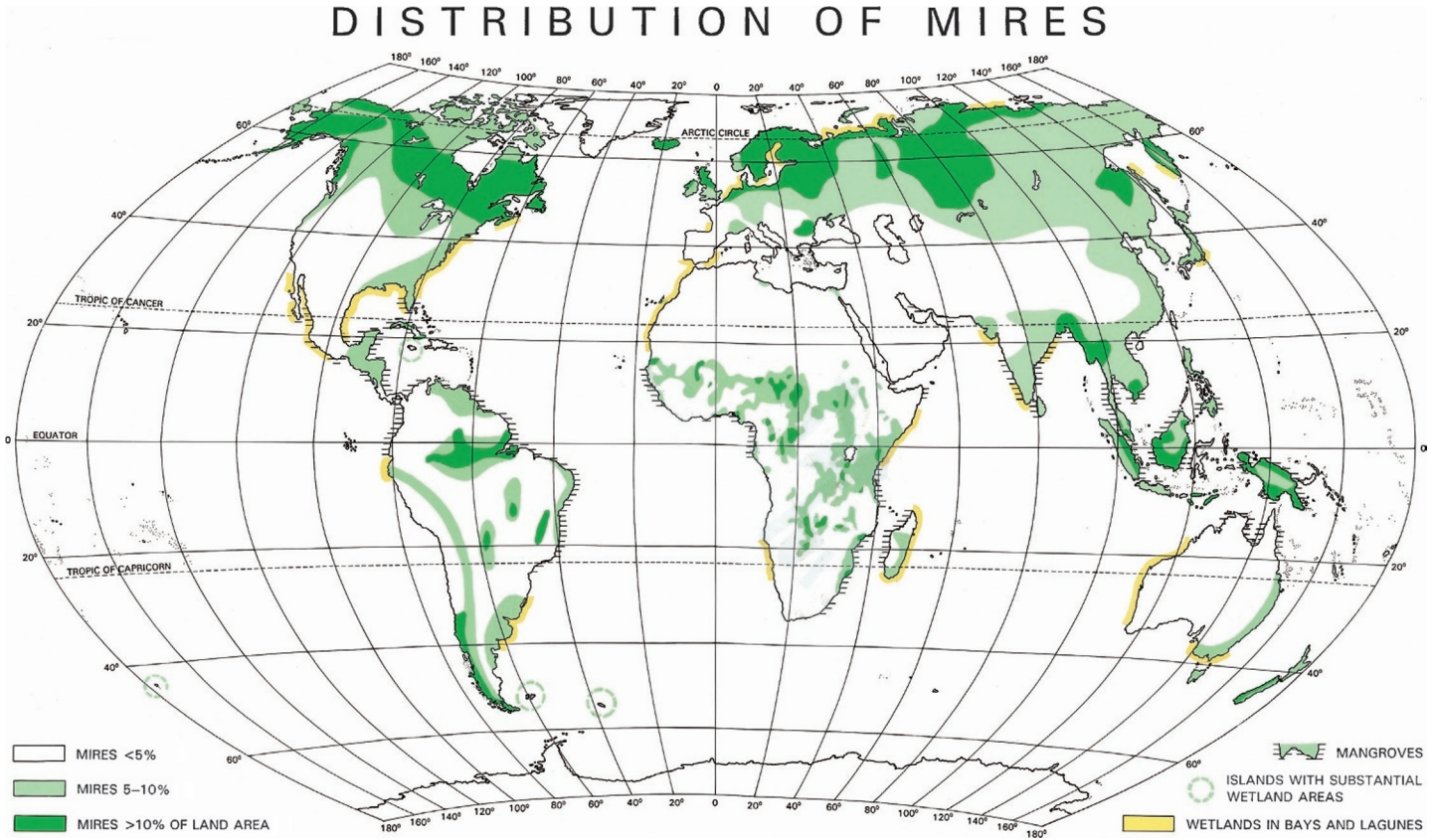


Fig. 3.36 Distribution of mires. Extent and location of global mires and peatlands (Lappalainen, 1996).

3.8.2.2 EU perspective

The European peatlands were mainly formed after the last Ice Age, with radioactive carbon (C^{14}) measurements in Estonia confirming this, with initial depositions from about 9100–8800 years ago. Peat deposits increase by about 0.5–0.9 mm/year, depending on climate and water conditions inside the soil, and deposition is greatest during chilly and rainy period (UT, 2016). The thickness of peat bed has an average of 4–5 m but in some places 7–8 m or even more (Eesti Turbaliit, 2016).

Relative covering (in%) of peat and peat-topped soils within the EU is shown on Fig. 3.37 (Montanarella *et al.*, 2006).

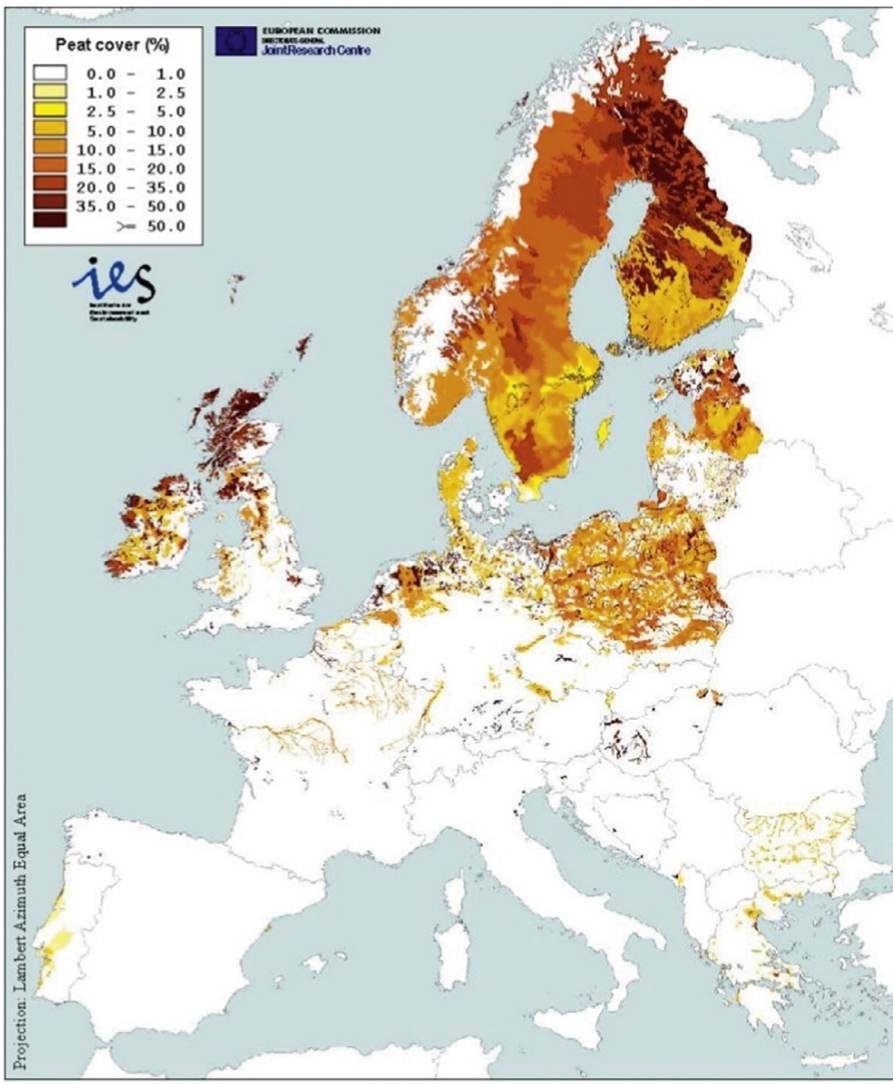


Fig. 3.37 Relative cover (%) of peat and peat-topped soils in the SMUs of the European Soil Database (Montanarella *et al.*, 2006).

3.8.3 Producing methods

The main methods of producing peat are by mechanically milling (Fig. 3.38) or by carving the blocks (Fig. 3.39). The max pressure of the machines used on peatlands is 18–20 kPa (Aro *et al.*, 1981). Peat contains about 90% water in bog, which must be removed prior to use, with the most effective method by drainage and exposure to sun and wind. Air-dried peat typically has a moisture content not more than 30%–40% (Eesti Turbaliit, 2016).

The partially decayed pocosin peat may also be used as insulation material. According to the Lennart von Post peat humification (H) scale (Damman and French, 1987), the best type of peat for carved blocks is from H2 (Almost entirely undecomposed peat

Fig. 3.38 Collecting dried milled peat from peat stack in Lavassaare peatland (Tootsi Turvas AS), Estonia (UT, 2016).

Fig. 3.39 Carved drying block peat in Lavassaare peatland (Tootsi Turvas AS), Estonia (UT, 2016).

which, when squeezed, releases clear or yellowish water. Plant remains still easily identifiable. No amorphous material present.) to H4 (Slightly decomposed peat which, when squeezed, releases very muddy dark water. No peat is passed between the fingers but the plant remains are slightly pasty and have lost some of their identifiable features.) or from H4 to H6 (Moderately highly decomposed peat with a very indistinct plant structure. When squeezed, about one-third of the peat escapes between the fingers. The residue is very pasty but shows the plant structure more distinctly than before squeezing.) if the peat is milled and mixed with other components.

3.8.4 Properties of peat

The physical, chemical and technological properties of peat are good enough for its use inside or as covering on timber structures.

Chemical properties

Peat is an organic material with a high water content (88%–92%), typically consisting of carbon (50%–60%), hydrogen (5%–7%), nitrogen (2%–3%), phosphorus (<0,2%) and oxygen and mineral nutritional elements; it does not have more than 35% of dry ingredient weight mass (UT, 2016).

Peat resists mould and microbes because it is a sour fibre by nature and contains some alcohol-based natural impregnating toxins. The pH of pocosin peat is low (3.5–4.0) (Berge, 2000) or even less.

Mechanical properties

The density of peat (dry weight) is usually between 100 and 200 kg/m^3. The compressive strength of pressed peat products depends on density, moisture content and proportion of mixture and is usually between 0.34 and 0.42 MPa.

Thermal and moisture properties

The thermal conductivity of insulation plates (pure peat or mixture with timber fibre) is good, between 0.037 W/mK (at density of 48 kg/m^3) (Konto Oy, 2015) and 0.08 W/mK (density of 275 kg/m^3) (Otloot and Veski, 1952) depending on density, moisture content and proportion of mixture. Pressed blocks or plates tolerate moisture and water extremely well and do not require any vapour barrier, but have the ability to aggregate exceeding moisture without risk of condensation and deterioration and release it back to the interior if the air becomes dry.

Fire resistance

The fire resistance of natural peat itself is not good (class E), but the material can be treated with the same impregnating agents as timber already during the element-producing process. The flashpoint of the air-dried peat is about 225°C. The initiation of thermal decomposition begins at around 100–110°C (Strandberg, 2014), whilst the charring temperature is 120–150°C (Berge, 2000).

Protection from radon

Peat is capable to filtrate and aggregate radon (Berge, 2000) and can be very useful for insulating floors from ground-source radiation because of this.

Rodent resistance

From the results of experiments (through three test periods, each 1 month) in the EstUnivLifeSc about the behaviour of black rats (*Rattus rattus*) inside different thermal insulation as bulk materials, peat was found to be the second best after EPS 50 (the worst were hemp chips and mineral wools) (Table 3.6; Paulus, 2011).

Technological properties

Pressed peat is easy to handle (lightweight) on the building site with ordinary timber tools (sawing, planning and routing), and structures can be puttied and coloured directly (Tehnika ja Tootmine, 1980). The material does not change form in different temperatures and is recyclable after use as heating material or in gardening.

3.8.5 Using peat in building structures in the past

The most common way of using peat for building structures in the past was covering the roofs together with grass (as done by the Saami people in Scandinavia and Iceland). Another method was to use peat blocks together with timber frames founded in Northern Europe as far back as the Iron Age. Today, it is common only in Iceland and Faroe islands. The turf-house tradition is now on World Heritage List Nominations.

The end of 19th and the beginning of 20th century saw increased demand for cheap apartment houses, which was met with frame-house technology that required insulation materials. One material used was milled peat, often mixed with sawdust or shaving. This material was replaced in the early 20th century with peat plate production, which helped to maintain comfortable temperatures inside buildings.

Table 3.6 Choosing of materials by rodents in point system (Paulus, 2011)

Insulation material	1. Test period	2. Test period	3. Test period	Total
Hemp chips	1	1	1	3
Glasswool (Isover KL 32)	2	3	2	7
Rockwool (Paroc UNM 37)	3	2	3	8
Cellulose (loose-fill)	4	4	4	12
Reed chips	5	5	6	16
Boob of flax	6	6	5	17
Sawdust	7	7	7	21
Peat	8	8	8	24
EPS 50	9	9	9	27

Interpretation: more points, lower/worse; less points, higher/better result.

3.8.3 Current peat production techniques

The best way to use peat in the timber-frame structures is as blocks from the natural biomass rich in moss (Fig. 3.40), which can be incorporated into cavities in walls. The peat can be mixed together with sawdust and/or shavings or with hydrated lime (<5%). The same mixture can be used in pressed peat plates used as roof covering, under flooring or as insulating material on or inside walls (Fig. 3.41).

3.8.7 Novel technologies of using peat

Because of continued development in the automatisation of processes and better knowledge of physical and chemical properties of peat, new opportunities have arisen, such as several patents for the use of peat in civil engineering projects.

Fig. 3.40 Dried block-peat in Lavassaare peatland (Tootsi Turvas AS), Estonia (UT, 2016).

Fig. 3.41 Konto-insulation plate of peat and timber fibre; thickness 50 and 75 mm (Konto Oy, 2015).

Table 3.7 Properties of peat product depending on type of technological water (Patent RU2514973 (C1), 2014)

	Ordinary, acidic	Magnetically activated, alkaline	Magnetically activated
Compressive strength (MPa) (10% linear deformation)	0.54	1.8	1.9
Bending strength (MPa)	0.26	0.46	0.49
Mean density (kg/m^3)	232	240	245
Water absorption (%)	88	90.5	71.5
Thermal conductivity (W/m°C) (in dry condition)	0.047	0.048	0.048

The risk of subsidence of milled peat after installation can be prevented with different mixtures and a novel technology together with magnetically activated water (Table 3.7).

The most novel technology being developed in Estonia is the use of structural 3D printing. The thermal, moisture and mechanical properties of material for such purposes in external walls are better than minimum construction standards and enable manufacturers to print out full houses even for different climate conditions. (Ecoconstruct, 2014). 3D printing of mixture of peat is very useful for building long-span double-twisted shell structures combined with timber parts because of its light weight.

3.8.8 Conclusion

The use of peat as a bio-based thermal insulation is well known historically, with many buildings still in existence.

The thermal properties of peat are known to be good enough and can compare with mineral wools for producing different types of insulation. Some results of testing main insulation materials in Estonia are given in Table 3.8.

The mechanical properties of pressed elements made of peat are sufficient for their use as structural load-carrying material at least for single-storey buildings without timber frame. Fire resistance can be increased by treating with impregnates or through the dry method of producing elements. The best and extraordinary characteristic is the favourable behaviour of peat in different moisture conditions compared with mineral wools, especially glass wools.

The other important thing is the possibility to use peat and its mixtures with novel technologies as 3D printing to construct more industrially and cheaper without losing the effectiveness of the material natural properties at the same time.

The resurgence of using peat for building purposes has already started in several countries (Sweden, Finland, Estonia, Russia, etc.). A significant number of scientists of northern countries are investigating the extraordinary properties of peat enhanced through the use of high-tech equipment.

Table 3.8 Thermal properties of main known insulating materials (Miljan and Miljan, 2012)

	Density r (kg/m^3)	Water content w (%)	Thermal conductivity l (W/(mK))
Isover OL-P	74		0.034
EPS	17		0.038
Isover (loose-fill)	50	0.6	0.039
Cellulose (loose-fill)	50	9.1	0.044
Cellulose (loose-fill)	30	7.6	0.045
Rough peat (milled)	135	5.5	0.046
Shaving	69	8.7	0.047
Fine peat (milled)	164	9.1	0.050
Boob of flax	109	8.4	0.050
Boob of hemp	94	8.2	0.053
Hemp chips	64	8.5	0.056
Sawdust	197	9.5	0.062
Isover (loose-fill)	30	0.3	0.065
Termoliit (sawdust + hydrated lime 5%)	254	5.7	0.066
Reed mat	119	5.4	0.070
Reed mulch	76	7.8	0.074
Hemp fibre	38	7.2	0.079
LECA (expanded clay) 10–20 mm	279	0.1	0.116

It is necessary to investigate the properties of insulation material of peat with different other components in depth as stability in time, resistance to the different weather conditions and behaviour in it, sound insulation qualities, the ability of biological resistance and behaviour with changes in temperature and humidity conditions through future field tests.

Fortunately, a lot of old buildings have survived in many countries to allow us to know/remember the possibilities to use peat in an environmentally friendly and sustainable way.

3.9 Grass

T. Teppand
Estonian University of Life Sciences, Tartu, Estonia

3.9.1 Introduction

Grass is a worldwide natural resource and renewable material. It is mostly used for agricultural purposes as feeding the cattle, as raw material for pharmacy (different

oils and extracts) and for food production (weeds and herb teas). Today, the biomass of herbs is also used to produce bioenergy just through the burning or treating it to biofuel.

The vegetation productivity of meadow herbs is very different in the world and in the EU, depending on exact climate zone and site class of soils, its pH and thermal and moisture conditions. It also depends on the relationship between species.

Years ago, it was common to use hay as temporary insulation during the winter in attics, whilst many seaside countries used eelgrass for similar insulating purposes.

Amongst recent studies into opportunities for grasses and herbs is one by the Estonian University of Life Sciences (EstUnivLifeSc), which aimed to find out the possibilities to make natural insulation materials from herbs and grasses from nonused fertile or nonfertile grassland. Such products may help reduce CO_2 emissions, together with retaining the nonused agricultural land.

Many nonfertile soils in northern countries are not used for agricultural purposes today compared with previous centuries. Most of these areas were used as hayfields or pasturelands in the past. These areas help in maintaining the biodiversity of the local environment but offer opportunities for harvesting, with some governments providing subsidiaries for mowing such lands at least once a year and to harvest it (Fig. 3.42). Currently, this material (of too low a nutritional level for cattle) is used for local bioenergy, since transport is too expensive for major use compared to the calorific value present.

The concept developed in Estonia was to use the biomass of specific herbs directly as loose-fill insulation material as done historically or to mix with other agents to get create new composite materials. Materials more suited to composites are species with properties like fibrous structure with closed cells, rigidity, cellular humid absorbency, less microparts during shattering, etc.

3.9.2 Species of herbs for testing thermal conductivity

Different species of herbs were harvested as part of the investigation (Table 3.9; Veri and Teppand, 2014), with material collected from a range of sites from fertile to nonfertile lands and from dry to flood-prone lands.

Fig. 3.42 Harvested and collected hay bales. Endla meadow, Estonia. Author's photo, 2016.

Table 3.9 Species of harvested herbs collected for tests (Veri and Teppand, 2014)

	Herb name (in Latin)	Herb name (in English)
1	*Galega orientalis*	Eastern galega
2	*Phalaris arundinacea*	Reed canary grass
3	*Urtica dioica*	Stinging nettle
4	*Aegopodium podagraria*	Ground elder
5	*Filipendula ulmaria*	Meadowsweet
6	*Humulus lupulus*	Common hop
7	*Carex nigra*	Common sedge
8	*Galinsoga quadriradiata*	Hairy galinsoga
9	*Chenopodium album*	White goosefoot
10	*Vicia faba*	Field bean
11	*Echinochloa crus-galli*	Cockspur grass
12	*Scirpus sylvaticus*	Wood club-rush
13	*Equisetum fluviatile*	Water horsetail
14	*Medicago sativa* ssp. varia	Sand lucerne
15	*Echinops*	Globe thistle
16	*Bromus inermis*	Bromegrass
17	*Cirsium arvense*	Creeping thistle
18	*Melilotus albus*	White sweet clover
19	*Chamaenerion* (Chamerion)	Rosebay willowherb
20	*Epilobium*	Willowherb
21	*Convolvulus arvensis*	Field bindweed
22	*Brassica napus*	Rapeseed
23	*Euphorbia helioscopia*	Sun spurge
24	*Lysimachia vulgaris*	Yellow loosestrife
25	*Sinapis arvensis*	Field mustard
26	*Calamagrostis epigejos*	Wood small-reed
27	*Typha latifolia*	Broadleaf cattail
28	*Festuca rubra*	Red fescue
29	*Deschampsia cespitosa*	Tufted hairgrass
30	*Trifolium medium*	Zigzag clover
31	*Scirpus sylvaticus*	Wood club-rush
32	*Arctium tomentosum*	Woolly burdock
33	*Solidago canadensis*	Canadian goldenrod
34	*Phaseolus vulgaris*	Common bean
35	*Tanacetum vulgare*	Common tansy
36	*Tripleurospermum inodorum* (*Matricaria perforata*)	Baldr's brow

A climate chamber and drying box were used for testing, with specimens of $295 \times 295 \times 100\,\text{mm}^3$ (Fig. 3.43).

Several agricultural techniques may be used to prepare the biomass. After that, blocks can be produced with adding adhesives and/or filling materials together with any necessary compression. Predrying of fibres is not necessary in cases where aqueous solutions (e.g. adhesives) are added prior to composite manufacture.

Fig. 3.43 Mixtures of mowing herbs with different binders in forms.
Author's photo, 2015.

3.9.3 Properties of biomass of mowing herbs

The physical, chemical and technological properties of biomass of mowing herbs are sufficient for their use as insulation material, especially inside structures of temporary or short lifespans, with service lives up to 50 years possible.

Thermal properties

Thermal conductivities between 0.034 and 0.09 W/(mK) were found for materials tested, comparable with other insulating materials.

Moisture conditions

The compressed blocks or mats tolerate moisture extremely well and do not require any vapour barrier, but have ability to absorb excess moisture without condensation and deterioration and desorb it back to the interior room conditions when dry.

Chemical properties

The processed raw material may comprise some agents for glueing or against decay (starch, dilute solution of polyvinyl acetate (*PVAC*) and boric salt).

Fire resistance

The reaction to fire of mown grass-made insulation materials is low (readily flammable (category E) according to EN 13501-1 (CEN, 2009), but the material can be treated with the same impregnating agents as timber already during the mixture-producing process.

The fire resistance of insulation products from marine products such as eelgrass is better because of salts present (Eriksen Hagen Stenberg *et al.*, 2008).

Mechanical properties

Subsidence after installation, a physical problem of chopped herbs used as a bulk material, can be prevented with different mixtures together with effective binders. The compressive strength depends of moisture content and of pressing value during producing. The pressed plates (see Fig. 3.44) have light densities, typically 35 kg/m^3 (Gramitherm, 2016). Pressed or sewed fibrous eelgrass plates (Fig. 3.45) resist vibrations very well.

Due to degradative risks from rodents, preventive methods are necessary to ensure the performance of the material. It means that the access of rodents inside structures (walls, under the floors and ceilings) needs to be effectively blocked (Konsa and Pilt, 2012).

Technological properties

The pressed materials of grass are easy to handle (lightweight) on the building site with ordinary timber tools (sawing, planning and routing). The material does not change form in different temperatures and moisture conditions and is recyclable after use as heating material or in the gardening because it does not contain harmful agents for environment.

Handling grass plates or mats is very convenient because the material is not itchy.

3.9.4 Using grass in building structures in the past

It was common for centuries to store hay (of meadow plants) on the attic of the houses out of town or barns to get better insulation of ceiling for underlaying rooms in regions

Fig. 3.44 Pressed insulation plates of mowing herb fibres with binder derived from starch (Gramitherm, 2016).

Fig. 3.45 Seaweed balls can be used as insulation free of chemical additives. Courtesy of Fraunhofer ICT 2013.

with humidity climate and big variations of temperature, particularly during the autumn and winter periods.

Mats of eelgrass were used for insulating the seats and perimeter of travelling coaches for centuries and then in walls of houses during the first half of 20th century.

3.9.5 Conclusion

From the results of tests in Estonia, it was shown that thermal properties of grass-made insulation materials were sufficiently good and comparable with mineral wools for use for producing different types of insulation (Table 3.10).

Good results could also be expected for biomass together with adhesive of PVAC dilute solvent, which is undergoing further testing to improve the technology to mix different chop and knead species assisted by self-adhesion. Another method is to merge fibres with starch to produce mats (Gramitherm, 2016). Composites made from grasses and herbs have been shown to have reasonable properties.

Fire resistance can be increased by treating with impregnates and/or with the help of covering plasters of clay and lime directly on the building site.

Insulation materials of grass (meadow herbs) and of eelgrass (genus *Zostera*) are good selections for ecologically friendly building solutions. The production cost is very low because of very low levels of processing energy (typically about 10 times less than conventional materials). The processes involved require little or no adhesives. The hydrothermal properties of grass-made insulation materials are good, whilst thermal conductivity can be compared with mineral wools. The material has both humidity absorption and desorption properties.

Through the correct implementation of these beneficial properties, it is hoped that opportunities for grasses and herbs may increase in the coming years.

Table 3.10 Comparative table of thermal conductivity (declared by special literature) of grass-made insulation through tests with other conventional materials

Material	Thermal conductivity (W/(mK))	Comments
Glass wool (wind screen)	0.031–0.033	
Sprayed rigid polyurethane (*PUR*)	0.033	
EPS	0.033–0.04	
Peat and timber fibrous plates[a]	0.034	
Rock wool	0.034–0.05	
Glass wool	0.035–0.06	
Biomass, test 4[b]	0.04	Hayfield association
Hemp wool	0.04	
Gramitherm[c] (natural grass 'silage')	0.04	
Eelgrass plates[d] (covered with paper)	0.041	*Zostera marina*
Cellulose (loose-fill)	0.044–0.045	
Biomass, test 5[b]	0.05	Damp area association
Biomass, test 2[b]	0.05	Globe thistle
Autoclaved aerated concrete[e] (Aeroc EcoTerm plus, 1.8 MPa)	0.072	
Biomass, test 9[b]	0.08	Biomass + PVAC solvent
Biomass, test 1[b]	0.09	Cockspur grass
LECA fill (expanded clay)	0.09–0.16	
Timber	0.12–0.14	
Autoclaved aerated concrete[e] (Aeroc Hard, 5.0 MPa)	0.13	
LECA 3 blocks (3.0 MPa)	0.2	
LECA 5 blocks (5.0 MPa)	0.24	

[a] Declared by Konto Oy (2015).
[b] Testing results (Veri and Teppand, 2014).
[c] Gramitherm (2016).
[d] Jürgenson (1942a,b).
[e] Declared by Aeroc International (Aeroc, 2016).

3.10 Vegetal pith

M. Palumbo, A.M. Lacasta†*
*Federal Fluminense University, Niterói, Brasil
†Polytechnic University of Catalonia, Barcelona, Spain

3.10.1 Introduction

The term vegetal pith is used here to refer to the parenchyma tissue present in the pith, the innermost layer of stems of many plants, and the aerenchyma, a specific type of parenchyma, which is found also in leaves and other parts of plants. The

parenchyma is a fundamental vegetal tissue consisting primarily of parenchyma cells. These cells are characterised for being highly unspecialised in structure and for having large central vacuoles and a thin and low-lignified flexible cell wall, perforated with plasmodesma, which allow for the intercellular communication and circulation of substances. Parenchyma cells are typically alive in maturity and conduct most of the plant's metabolic functions, such as storage of energy (mainly in the form of starch and fats) and waste products (tannin, resins, gums, etc.), support for photosynthesis (as are the cells containing chlorophyll), gaseous exchange (which takes place in the intercellular spaces) and damage repair. Moreover, parenchyma cells have an important structural role in maintaining shape and firmness of the plant or providing aeration and buoyancy in aquatic plants (Alberts *et al.*, 2010).

The vegetal pith is formed by the largest parenchyma cells in the plant and is characterised for being light and spongy. It may be a compactly packed tissue in which the cells are joined by their middle lamella or a loose structure, with extensive voids between cells.

Several food and industrial crops, such as corn (genus *Zea*), sorghum (genus *Sorghum*), pearl millet (genus *Pennisetum*), sunflower (genus *Helianthus*) or elephant grass (genus *Miscanthus*), are sources of vegetal pith. Wetland plants commonly used for wastewater treatment, such as cattails (genus *Typha*) and some bulrushes (mainly in the Cyperaceae family), are alternative sources of vegetal pith.

Vegetal pith is a widely available, easily accessible resource, which is nowadays undervalued. However, its intrinsic properties, given by its structure and chemical composition, are promising for its use in building applications, especially in thermal insulation purposes. Certainly, innovative and highly valuable vegetal-pith-based products are and will increasingly continue to be developed in the coming years.

3.10.2 Sources of vegetal pith

There are many plants that can be source of pith. Cornstalk consists of a solid cylinder of pith traversed longitudinally by scattered vascular bundles. The nodes constitute about 26% of the weight of the stalk, the shell of the internodes about 54% and the pith about 20%. About 60%–70% of the internode cylinders consist of fundamental parenchyma (Hooper, 1930). Pith is also found in the interior of corn cobs (Pinto *et al.*, 2011). Sorghum stalks are composed of pith and bark, which are present in approximately equal quantities (Billa *et al.*, 1997). In the case of sunflower stalks, pith accounts for about 35% (Magniont, 2010). An experiment by Kaack *et al.* (2003) showed that the percentage of pith in miscanthus stalks varied significantly with the internode, increasing from the lower to the upper, indicating that the pith disappears with the age of the internodes. A percentage of 58% was obtained for the sixth internode. Many aquatic plants can be also an interesting source of plant pith. *Typha* (*Typha angustifolia* and *Typha latifolia*), also known as cattail, is composed of aerenchyma tissue in approximately 85% of the plant mass. Similar percentages of aerenchyma tissue can be found in totora.

Within the above-mentioned plants, the ones that are growth for food grain (corn, sorghum and sunflower) are worldwide harvested in large quantities. According to FAO data, in 2014, the world production for corn, sorghum and sunflower was of 1022, 68 and 41 million tons, respectively, with the distribution shown in Fig. 3.46, which shows that corn is mainly produced in America and Asia, sorghum in Africa and America and sunflower in Europe.

Corn is believed to have originated in central Mexico 7000 years ago, from a wild grass and domesticated by Native Americans. Nowadays, it is the cereal with the largest production volume worldwide. The United States, China and Brazil are the top three corn-producing countries in the world, producing approximately 563 million t/year, both for human and animal feeding. For animal feeding, two harvesting periods are possible: when the plant is still green or when it is ripened. In the first case, the whole plant, including stalks, is harvested and chopped. In the second case, which is the most usual, the cobs are pulled out of the stalks, which are left in the field. The product obtained by this process is of higher quality. The stalks are balled and used in pellet production or buried in the fields and thus valuated for their humic and mineral content.

Sorghum is an indigenous crop to Africa and is the fifth most cultivated cereal crop worldwide. It is Africa's second most important cereal with a production of some 20 million t/year. Sorghum is drought resistant, can withstand water logging from heavy rain and can grow in both temperate and tropical zones (Stone *et al.*, 2011). Long established in Asia and Africa, sorghum has now become important in Latin America as well.

Sunflower is widely cultivated all over the world. In 2010, the harvested area in Europe was 3.68×10^6 ha. representing 16% of the total harvested area in the world (Sun *et al.*, 2013). The crushed sunflower stems have no real application in agriculture, and it has been estimated that each hectare of sunflower can produce 3–7 tons of dry biomass including stems (Mati-Baouche *et al.*, 2014).

The genus *Miscanthus* comprises a group of more than 10 rhizomatous grass species, most of which are native to Asia. Miscanthus is a perennial grass that produces very high yields of bamboo-like canes up to 3 m tall (Salvadó *et al.*, 2003). It

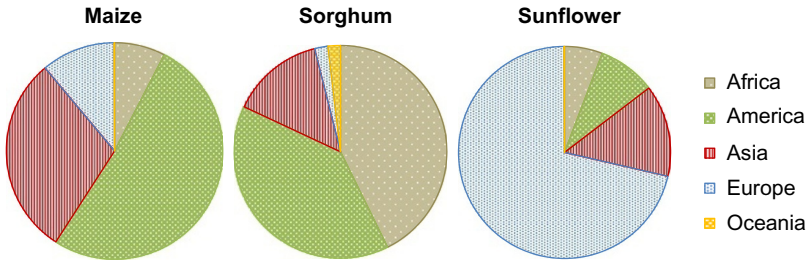


Fig. 3.46 Distribution of the production of three crops rich in pith.
Data from FAO-FAOSTAT (http://faostat3.fao.org/), year 2014.

is native to eastern Asia throughout most of China, Japan, Taiwan and Korea, where it is used mainly by the paper industry to produce low- and medium-quality printing paper. For this use, the fibres are valuable, but the presence of pith is a drawback and influences the quality of the paper. In Europe, miscanthus is mainly used to produce energy.

Typha is a genus of about 30 species in the family Typhaceae. The genus is largely distributed and is found in a variety of wetland habitats. Typha stock comprises resilient, natural monocultures with an annual production rate of 15–20 tons of dry matter per hectare (Krus *et al.*, 2015). Although typha are native wetland plants, they can be aggressive in their competition with other native species. Narrow-leaved cattail (*T. angustifolia*) is a marginal weed, which originated in Europe and America and spread in tropical areas such as Thailand, Malaysia, Philippines, North America and Pacific coast. Broad-leaf cattail (*T. latifolia*) is found as a native plant species in North and South America, Europe, Eurasia and Africa. It is an introduced species in Australia, New Zealand and some Asian countries such as Indonesia and Philippines. Totora (*Schoenoplectus tatora*) is found in South America, notably on Lake Titicaca.

Despite its distinct structure and properties, vegetal pith is still rarely used isolated from the rest of the plant tissues. Thus, there is still margin of improvement on the separation techniques. Balducci *et al.* (2008) milled the whole stalks and tried to separate the pith material by wind sifting with a zigzag sifter. Unfortunately, the process was insufficient to separate pith efficiently. Cundiff and Worley (Cundiff and Worley, 1992) analysed the chopping parameters for separation of sweet sorghum pith and rind-leaf. In this study, sorghum stalks were chopped using different knife velocities and chop intervals. The resulting mixture of short pith particles and longer rind-leaf fibres was separated using a manually vibrated screen. The use of a vibrating table has been proved to be effective on the separation of corn pith from the rest of the plant materials after hammermilling. Corn pith can also be obtained, adapting the decorticator machines mainly used for sugarcane. An example of this is the system developed by Tilby technologies (http://www.tilby-technologies.com/), which returns four different products (amongst which, vegetal pith) from the plant stalks.

3.10.3 Morphology and characterisation of vegetal pith

3.10.3.1 Morphology of vegetal pith

As mentioned before, the term vegetal pith is referred to parenchyma tissues characterised for being light weight, low lignified and spongy. A wide diversity of vegetal-pith structures exists in nature, which differ from one species to the other and according to their function in the plant. Some examples of vegetal-pith structures are presented in Figs 3.47 and 3.48. The images are presented at the same scale.

From the images, it appears that corn and sorghum have a similar vegetal-pith structure, which forms a rather homogenous net surrounding several evenly distrib-

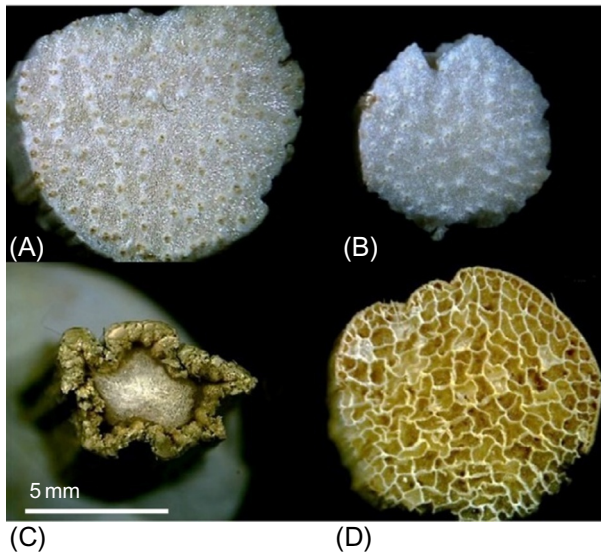


Fig. 3.47 Images of cross sections of (A) corn, (B) sorghum, (C) sunflower and (D) totora stems.

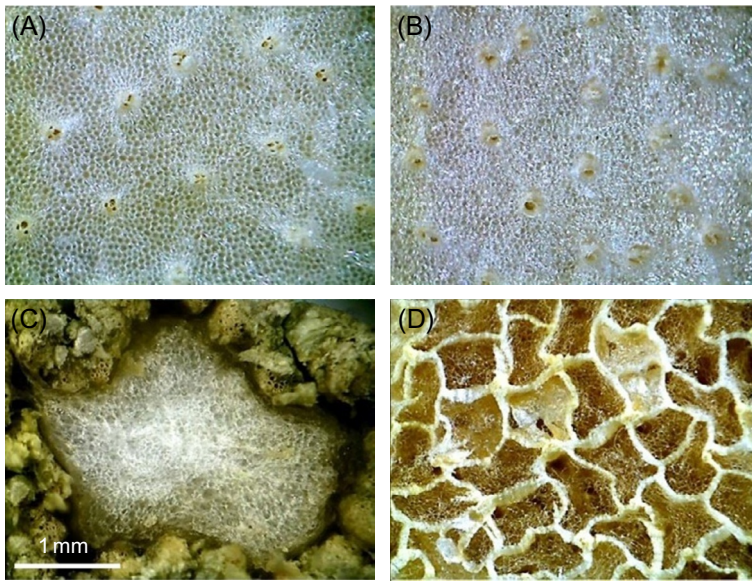


Fig. 3.48 Magnified images of cross sections of (A) corn, (B) sorghum, (C) sunflower and (D) totora stems.

uted vascular bundles. The vegetal pith is composed by rather oval parenchyma cellules with a diameter of about 100–140 µm and thin cellular walls (width of about 0.4 µm). The intercellular spaces that are formed at the edges of the contacts between cells have a diameter of about 10 µm. The cells are interconnected through

plasmodesmata with diameter of about 2 µm (Palumbo *et al.*, 2015b). Vascular bundles are not present in sunflower pith. In fresh stalks, the pith and the cortex tissues form a continuum. However, the external part of the stalks suffers severe shrinkage due to dehydration, dissociating from the internal pithy part and causing its compression. The vegetal piths of totora and cattail are aerenchyma tissues and thus have a noticeable different structural organisation. In both cases, two hierarchies exist. The highest one corresponds to a neural structure (isotropic in the case of totora and linear in the case of cattail) composed mainly by fibre chains in between, which a second-order grid is formed.

3.10.3.2 Chemical composition

From the point of view of chemical composition, vegetal pith can be classified as a lignocellulosic material. Lignocellulosic materials are characterised for being composed mainly by three polymers: two carbohydrates, cellulose and hemicellulose; and an aromatic polymer, lignin. Other substances, such as waxes, tannins or minerals, are also part of lignocellulosic materials but in smaller quantities. The proportions in which the three main polymers in lignocellulosic materials are found largely vary between one species to the other, between different specimens of the same species, between different parts of the same specimen and between different maturity levels of the same part of the plant. Moreover, sample preparation and the methods used to prepare and characterise the materials may change, affecting the outcomes (Lee *et al.*, 2007). This results in an important dispersion of the values reported by different authors, which is depicted in Table 3.11.

Table 3.11 Chemical composition of different vegetal piths reported by various authors

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Crude protein (%)	Ash (%)
Corn stover[a]	38	26	23	5	6
Miscanthus[a]	43	24	19	3	2
Forage sorghum[a]	34	17	16	-	5
Sweet sorghum[a]	23	14	11	-	5
Pearl millet[a]	25	35	3	10	9
Sudan grass[a]	33	27	8	12	12
Topinambour stalks[b]	30.9	17.1	16.3	-	-
Sunflower stalks[b]	40.9	19.4	21.6	-	-
Sunflower stalks[c]	38.6–42.1	22.8–29.7	13.4–16.2	-	8.9–12.2
Sunflower pith[c]	47.4	9.4	3.5	6	20.4

[a] Values reported by Lee *et al.* (2007).
[b] Values reported by Klímek *et al.* (2016).
[c] Values reported by Nozahic *et al.* (2012).

Nozahic *et al.* (2012) reported a similar chemical composition between hemp hurds and sunflower stems, with exception of lignin and pectin contents, which were higher in hemp hurds. When isolated, sunflower pith revealed to be a lignin weak product (3.5%).

The chemical composition of the raw materials may influence the properties of the products manufactured from them. Holocellulose (cellulose and hemicellulose) is considered to be responsible for the bonding with polar adhesive polymers and water absorption. On the contrary, lignin is more hydrophobic and thus contributes to restrain water uptake. The presence of extractives may also be influent. However, how the chemical composition of the raw materials affects the performance of the derived products is not yet fully understood, as the complex and interconnected effects are difficult to isolate (Klímek *et al.*, 2016).

3.10.3.3 Thermal properties

Several authors have analysed the thermal properties of vegetal piths under the assumption that the nature of its structure would give it a high thermal insulation capacity. Table 3.12 summarises the thermal conductivities reported for different vegetal piths. Pinto *et al.* (2011, 2012) analysed the structure of the vegetal pith present at the inner part of corn cobs and found evident similarities both in shape and size of the cells, with expanded polystyrene (EPS). Palumbo *et al.* (2015b) analysed the thermal conductivity of corn-pith aggregates with different particle sizes. The pith was obtained from the inner part of the stalks and manually isolated from the cortical fibres. It was found that the thermal conductivity of corn pith was 0.048 W/mK, 10% lower than that of barley straw fibres. Moreover, it was observed that thermal conductivity was not affected by particle size in corn-pith aggregates, which was not true for straw fibres: smaller particle size resulted in higher thermal conductivity. The bulk densities reported were in the range of 37 kg/m^3. Similarly,

Table 3.12 Thermal properties of different vegetal-pith aggregates

Crop by-product	Particle size (mm)	Thermal conductivity (W/mK)	Thermal diffusivity (10^6 m^2/s)	Bulk density (kg/m^3)
Sunflower (Magniont, 2010)	–	–	–	35
Sunflower (Nozahic *et al.*, 2012)	–	–	–	105
Typha (Diatta *et al.*, 2011)	–	0.045	–	69.7 ± 0.01
Typha (Georgiev *et al.*, 2014)	–	0.032	–	30
Corn (Palumbo *et al.*, 2015b)	2.0 1.0 0.5	0.048 ± 0.002 0.047 ± 0.003 0.048 ± 0.001	0.114 ± 0.007 0.107 ± 0.001 0.133 ± 0.010	37 ± 1 36 ± 1 37.8 ± 0.8

Diatta *et al.* (2011) investigated the thermal conductivity of typha aggregates. The aggregates were prepared at different compactions to determine the variation of thermal conductivity with density. The values of density and thermal conductivity ranged from 57.5 to 81 kg/m^3 and from 0.039 to 0.056 W/mK, respectively. The thermal conductivity increased linearly with density. Much lower values were reported by Georgiev *et al.* (2014).

All the results indicate that vegetal pith naturally has a low thermal conductivity, similar to engineered thermal insulation materials.

3.10.3.4 Hygroscopic and sorption properties

Vegetal pith is characterised for having a high hygroscopicity, this means that it has the capacity to sorb and desorb moisture from and to its internal porous structure, establishing a hygric balance with its environment (Korjenic *et al.*, 2011). Indeed, vegetal pith can be regarded as a dynamic three-phase system: a mix of cell walls (solid phase), water (adsorbed on the surface and within the cell walls, liquid phase) and air and water vapour (present within the pores, gaseous phase), which is in constant equilibrium with the environment. This is an important property in building applications as it may impact indoor thermal comfort and energy efficiency.

The hygroscopicity of a material can be determined by its sorption isotherm. That is, the relationship between the water content of the material and the relative humidity of its environment at a certain constant-temperature and steady-state conditions. The sorption isotherm can be determined experimentally by exposing the material to an environment where the relative humidity is controlled. The moisture content of the material is determined gravimetrically. When the system reaches hygric equilibrium, that is, the weight of the materials is constant, the relative humidity is increased and maintained until the hygric equilibrium is reached again. The relative humidity is increased successively by steps to reach ~95% and then decreased again likewise. This procedure is generally performed using the saturated salt solution method or with the aid of a DVS apparatus. The DVS is less time-consuming but uses small samples that might not be representative of the material. The reproducibility of this method is discussed by Hill *et al.* (2010). Using the saturated salt solution method, larger samples can be tested, but the time it takes for stabilisation is longer, in the order of several months (Magniont, 2010).

The shape of the isotherm depends on the porous structure of the material. Vegetal pith, as other lignocellulosic materials, shows a sigmoidal-shaped isotherm with hysteresis. However, important differences can be regarded between different vegetal piths depending on their source. Fig. 3.49 shows the sorption isotherms obtained for miscanthus pith and corn pith when subjected to different environments using the saturated salt solution method. The moisture content of the materials is the same at low relative humidity (32%). However, as relative humidity increases, corn absorbs higher amounts of moisture, up to 26% its dry weight.

The liquid water absorption of sunflower vegetal pith and hemp hurds was analysed by Nozahic *et al.* (2012). The authors report a faster and higher moisture uptake of sunflower pith, which was evident only after the first 5 min of the experiment.

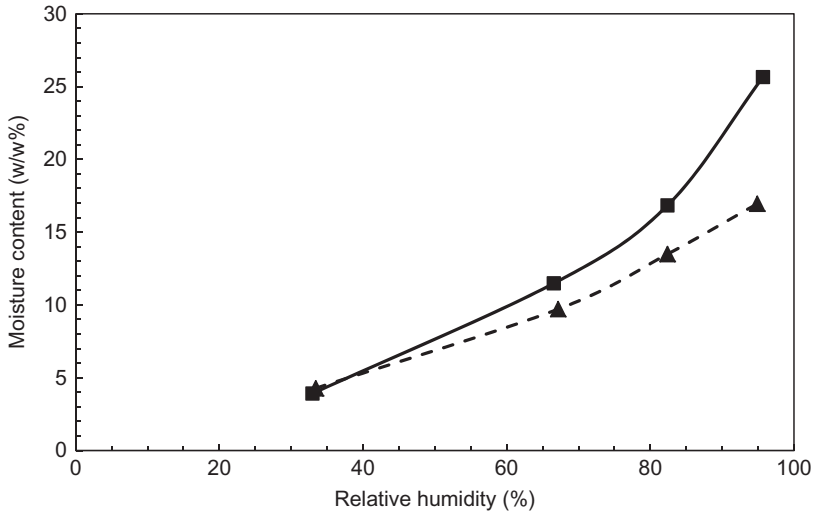


Fig. 3.49 Sorption isotherms (20°C) of corn pith (solid line) and miscanthus pith (dashed line).

3.10.3.5 Thermal degradation

Thermal degradation and fire behaviour of lignocellulosic materials are important issues to consider when envisioning building applications. Heat release rate (*HRR*) curves and total heat release (*HR*) can be determined, for small samples, using a microcalorimeter device known as pyrolysis combustion flow calorimeter (*PCFC*). In this technique, the samples are placed in a pyrolyser, in a nitrogen atmosphere, with a heating rate of 60°C/min up to a maximum temperature of 750°C. Products from the anaerobic thermal degradation are mixed with a stream of oxygen prior to entering the combustion furnace at 900°C. HRR is determined from the oxygen consumption (Lyon and Walters, 2004).

Fig. 3.50 shows the HRR of pith samples from two different plants. The two samples show a clear peak, mainly as a result of the thermal decomposition of cellulose. The high-temperature tails that appear in all curves are associated with lignin, the degradation temperature range of which is wide, from 200°C to 500°C.

In all the cases, the maximum HRR is about 100 W/g, and the total HR, which is the integral of the HRR over the complete time of the test, is in the range of 8–10 MJ/kg. The lower HRR values observed for corn pith may be related with its higher water sorption, since HRR is given by unit of sample mass. Compared with other crop by-products, pith has a higher HR than rice husk and similar value than barley straw (Palumbo, 2015).

3.10.4 Vegetal pith as a building material

3.10.4.1 Thermal insulation boards

One of the major challenges of this industry for the next decade is to improve the energy performance of existing buildings, taking into account the increasing social emphasis on issues concerning the environmental impact, waste disposal and the

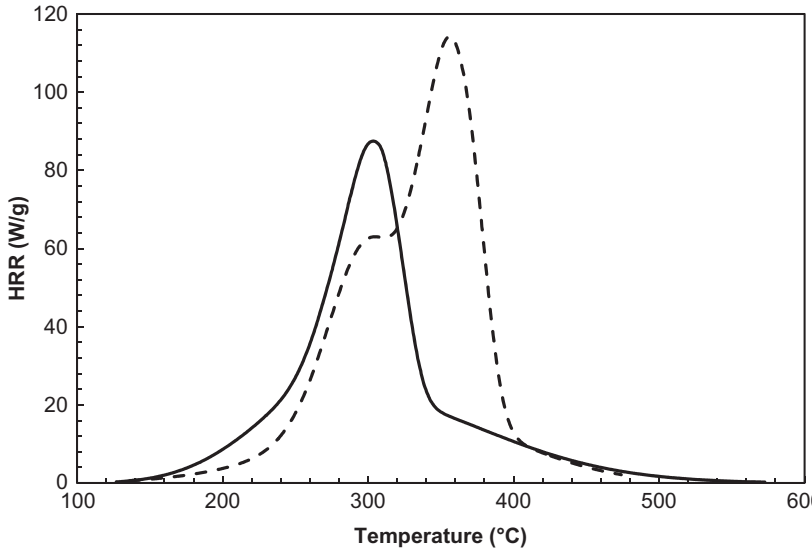


Fig. 3.50 Heat release rate for corn pith (solid line) and miscanthus pith (dashed line).

depletion of nonrenewable resources. The motivating factors include cost, mechanical, thermal and acoustic performance enhancements, weight reduction and the environment friendliness (Bolat, 2005). In this context, bio-based insulating materials made from by-products of agricultural waste constitute an interesting alternative to those obtained from fossil carbon (Binici *et al.*, 2016).

A material is considered as a thermal insulator when its thermal conductivity (λ) is lower than 0.1 W/mK, although commercially available insulation materials usually have lower thermal conductivity, below 0.06 W/mK. Thermal conductivity depends on several factors, but density is a driven factor. The very low density and high porosity of pith makes it suitable for this use (Asdrubali *et al.*, 2015). There are many examples of applications, currently in different stages of development.

Since some pioneering patents and research from the first decades of the 20th century (De Long, 1923; Hinde, 1927; Elmendorf, 1929; Sweeney and Emley, 1930) to the present, the viability of producing insulation boards from corn pith (stalks and cobs) has been investigated. Dowling and Mathias (2007) evaluated the thermal performance of grinded corn cob and determined that it is lower than that of conventional insulation materials. Pinto *et al.* (2011) found that corn cobs were used in traditional architecture to improve the thermal insulation of mud walls and developed cement-bonded boards based on corn cobs. More recently, Palumbo (2015, 2015a,b, 2016) have recently developed insulation rigid boards based on corn pith agglutinated with sodium alginate, which is natural binder obtained from algae.

Rigid board specimens were made using corn pith that was manually removed from corn stalks, grinded and sieved to form a 4 to 2 mm granulate (Fig. 3.51). Physical properties and hydrothermal behaviour were evaluated and compared with other insulation materials (Palumbo *et al.*, 2015b). The board had a thermal conductiv-

Fig. 3.51 Rigid board made of corn pith and sodium alginate.

ity of 0.039 W/mK and a density of 60 kg/m^3. The dependence of thermal conductivity, thermal diffusivity and water vapour permeability with relative humidity was experimentally determined. Experimental moisture buffer values were obtained, and these values were compared with numerical results obtained from a dynamical model (Palumbo *et al.*, 2016). Thermal degradation and fire reaction were also evaluated, obtaining a quite positive behaviour (Palumbo, 2015). The HR measured with a PCFC for corn-pith panels with alginate was of about 6 MJ/kg, much slower than the HR obtained for other commonly used organic foams such as EPS or polyurethane (PUR), which give HR values of 38.7 and 13.3 MJ/kg, respectively. Recent fire tests using a cone calorimeter indicated an excellent behaviour of the corn-pith panel, both in terms of HRR (Fig. 3.52) and smoke production, when compared with EPS insulation. However, a smouldering combustion, characteristic of lignocellulosic materials, was also observed in some conditions. In a second stage of development, the corn-pith boards were pretreated with different substances, that is, boric acid, aluminium hydroxide, montan wax, acetic acid and lactic acid before forming the board in order to improve the smouldering combustion and fungal resistance of the material (Palumbo *et al.*, 2015a).

Luamkanchanaphan *et al.* (2012) studied the physical, mechanical and thermal properties of insulation boards prepared from narrow-leaved cattail collected at Chanthaburi Province in the east of Thailand. The boards were conformed using methylene diphenyl diisocyanate (*MDI*) as a binder and applying a hot-pressing method to obtain target densities of 200, 300 and 400 kg/m^3. The results indicated good physical, mechanical and thermal properties, with thermal conductivities in the range of 0.0438–0.0606 W/mK. Krus *et al.* (2015) recently developed a new magnesite-bound typha board (Typha panel) that combined high strength and dynamic stability with a low thermal conductivity of about 0.055 W/mK. According to the authors, this was possible due to the intrinsic structure of the typha leaf. The typha leaf is composed by a fibre-reinforced supporting tissue filled with vegetal pith, which makes it tear and break resistant, flexible and dimensionally stable in case of changes in moisture. In order to profit from these intrinsic qualities, typha leaves are cut longitudinally to form bars. The resulting boards are similar to OSB materials. These magnesite-bound typha

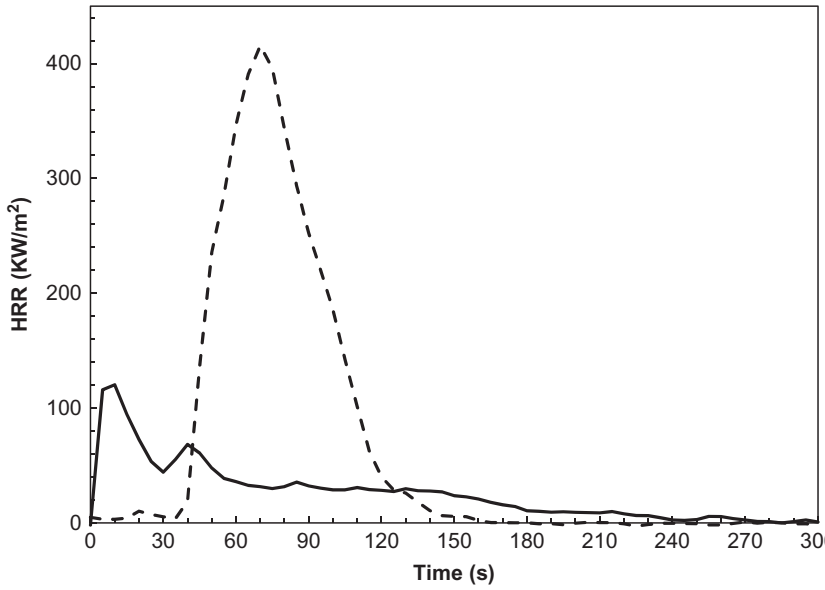


Fig. 3.52 Heat release rate (HRR) curved obtained in a cone calorimeter test for samples of EPS (dashed line) and corn-pith-based panels (solid line). The tests were performed at a heat rate of 50 KW/m^2.

boards were used in the restoration of an old half-timber-framed building in Nürnberg, Germany. The measurements of temperatures and humidity in various depths of the structure along 1.5 years proved the building physical suitability (Krus *et al.*, 2015).

Totora plants from Titicaca Lake, Peru, have been used for different types of insulation panels (Aza Medina, 2016). In addition to panels made from grinded and glued pith, similar to the corn panels shown in Fig. 3.51, an interesting kind of panel was developed from whole pieces of totora, arranged in three layers that were rotated 90 degree with respect to each other (Fig. 3.53). The pieces and layers are glued with natural binders such as bone glue or alginate. Both kinds of panels showed low thermal conductivities. In the case of crushed totora, depending on the particle size, thermal conductivities in the range of 0.045–0.048 W/mK were obtained, whereas for the whole pieces, somewhat higher values (about 0.050 W/mK) were measured.

Although insulation board is not expected to have important mechanical properties, it is important to guaranty a certain degree of resistance needed for handing and application. For these reason, totora samples with different compositions were prepared for strength test (Fig. 3.54). The mechanical resistance for the grinded totora samples was acceptable and for the three-layered pieces of totora were much better, obtaining values of about 10 times higher. Air permeability tests also showed excellent results for this configuration. Regarding the fire behaviour, totora showed a good behaviour, with small contribution to fire and an important self-extinguishing capacity (Aza Medina, 2016).

Vandenbossche *et al.* (2012) produced insulation panels with different agromaterials: sunflower, hemp, corn, wheat straw and rice hull. The influence of particles

Fig. 3.53 Low-density board made from whole pieces of totora plants (Aza Medina, 2016).

Fig. 3.54 From left to right, samples made from totora, after bending tensile strength test and detail of sample under test (Aza Medina, 2016).

size on thermal conductivity was studied in the case of sunflower pith. They found that an increase of particles sizes generates an increase of empty spaces and by consequence a decrease of the density. For each plant, the thermal conductivity increased proportionally with the density. The best results in terms of density and thermal conductivity were obtained with sunflower pith. No adhesive was necessary to format it. It was enough to humidify and to mould it to obtain a cohesive material easy to handle. Mati-Baouche *et al.* (2014) analysed the mechanical, thermal and acoustical properties of an insulating bio-based composite made from sunflower stalk particles and chitosan (a natural polymer obtained industrially by deacetylation of chitin from

crustacean shells). It was shown that the thermal and mechanical performances of the composites were proportionately improved with the increasing of compaction pressure. Composites with a thermal conductivity of 0.06 W/mK and a maximum stress at break of about 2 MPa were obtained with a ratio chitosan/sunflower of 4.3%, a particle size of shredded sunflower stalks of 6.3 mm and a density of 150 kg/m^3.

3.10.4.2 Particleboards

Each year, about 28.4 million m^3 of particle boards are produced in Europe mainly for furniture and building applications (Klímek *et al.*, 2016). Wood is the main raw material used to this end, although the feasibility of nonwood alternatives has been investigated for many decades. Recently, many drivers, including wood shortage, environmental awareness and low cost of nonwood materials, boosted not only for an intensification of this research but also for a major implication of industries.

In 2005, at least 30 industrial plants all over the world integrated the use of nonwood lignocellulosic aggregates in the production of particle boards (Bektaş *et al.*, 2005). Today, although the technical feasibility of nonwood particle boards is generally accepted (Bajwa *et al.*, 2015), further research is needed to fully understand how the intrinsic properties of the raw materials can contribute to enhance the overall performance of the engineered materials. The vast majority of the examples of nonwood particle board developments are focused on the use of different kinds of natural fibres. This is consistent with the fact that fibres make an important contribution to the enhancement of the mechanical properties of the boards. Fibrous materials from crop plants are preferred for their availability and easy accessibility. Examples are straw (from wheat, barley, rice, etc.), cotton gin or bagasse, coir and kenaf or banana fibres. Some investigations have been conducted in which vegetal pith-rich plants were evaluated; however, it is rare to find examples of the use of isolated vegetal pith in the manufacture of particle boards.

It is well known that particle size and shape affect the properties of the particle boards. Vegetal pith aggregates tend to form rather spherical particles, (Magniont, 2010; Palumbo, 2015, 2015a,b). Generally, more spherical particles have a positive effect on internal bonding (*IB*) but have a detrimental impact on MOR and MOE, which are more profiting from longer particles or fibres (Bajwa *et al.*, 2015; (Klímek *et al.*, 2016). Indeed, the presence of vegetal pith is reported to have negative effects on both MOE and MOR (Balducci *et al.*, 2008; Klímek *et al.*, 2016).

On the other hand, when vegetal pith is grounded together with the fibrous tissues of the plants, a mixture of spherical and elongated particles is obtained (Nozahic *et al.*, 2012). Such mixtures are unable to compactly pack in the boards, which dramatically reduces density and IB (Bajwa *et al.*, 2015). Such drawback could be compensated by reducing particle size, increasing the target density of the particle boards, lowering the board's thickness (Klímek *et al.*, 2016) or effectively removing vegetal pith before board formation.

Salvado *et al.* (2003) produced experimental binderless fibreboards based on miscanthus (*Miscanthus sinensis*). After harvesting, the miscanthus stems were cleaned and chipped. The chips were steam exploded with a thermomechanical aqueous vapour

process in a batch reactor to obtain a pulp. The resulting material was dried, slightly milled and used to produce the fibreboards. The pretreatment and the pressing conditions that optimise the physico-mechanical responses were determined. The boards obtained showed rather good results: a modulus of elasticity as high as 7630 MPa, MOR as high as 61 MPa, internal bond as high as 4.1 MPa, thickness swelling as low as 2.5% and water absorption as low as 8.9%. The average density of the boards was 1240 kg/m^3. Below 1100 kg/m^3, the boards did not succeed to fulfil the requirements for MOR established in EN 31094.

Bajwa *et al.* (2015) evaluated the feasibility of cattails for manufacturing particle boards for commercial applications. Straw- and cattail-based particle boards bonded with 3% of polymethylene diphenyl diisocyanate (*pMDI*) were manufactured using a hot-plate press (190°C and 1.54 Mpa for 420 s). The target density was maintained at 480 kg/m^3, and the proportion of cattail and wheat straw was varied between 100%, 50% and 25% to obtain four different formulations. Cattails (both stems and leaves) and straw were used in the form of chips of between 2 and 6 cm in size. It was found that the incorporation of cattails resulted in an improvement of the overall properties with respect to the control of 100% straw. However, the specimens of 100% cattail did not yield the best results either. The best results were obtained for mixtures of 70% cattails and 25% straw, which exhibited superior average flexural stiffness (MOE of 446.3 N/mm^2), flexural strength (MOR of 17.95 N/mm^2) and internal bond, and lower water absorption and thickness swelling. Besides, the dispersion of measured results was lower than for the rest of the formulations. Weak bonding between straw particles due to the presence of cuticular waxy layer was assumed to be the cause of the poor results obtained for the straw-based particle boards, whilst the poor results obtained for the 100% cattail samples were attributed to lose packing density of the randomly organised particles. According to the authors, the use of mixtures of cattail and straw aggregates for the manufacture of particle boards is feasible, and better results should be expected if the moisture content and particle sizes of the two aggregates are matched.

Binici *et al.* (2016) developed corn-cob-based composites and analysed the effect of particle size and matrix/aggregate ratio on the thermal, mechanical and acoustic insulation properties of the boards. Corn cobs were hammermilled and sieved to particles sizes between 1.6 and 6.3 mm and blended with an epoxy resin, added in 50% and 75% proportions and pressed for 1 min at room temperature and variable pressures (between 0.07 and 0.27 MPa). The resulting materials had densities ranging between 250 and 410 kg/m^3 and thermal conductivities between 0.159 and 0.075 W/mK. Pressure was found to be the main driving factor affecting the analysed properties: higher manufacturing pressure resulted in not only higher density and thus better mechanical properties but also higher thermal and sound conductivities.

Klímek *et al.* (2016) used two vegetal-pith-rich plants, sunflower (*Helianthus annuus*) and topinambour (*Helianthus tuberosus*), and a third nonwood plant, cup plant (*Silphium perfoliatum*), as raw materials for the production of particle boards. MDI and UF resins were used as bonding agents. The vegetal materials were hammermilled and sieved to obtain aggregates of 5 and 1.24 mm in size. The aspect ratio (ratio of length/width) of the aggregates was analysed. Whilst topinambour and cup

plant formed rather elongated particles, sunflower particles were 'cubicle', probably due to a lower amount of fibrous tissues and/or lower lignification of fibre bundles. The size dispersion in the aggregates was found to be higher than in wood chips. The aggregates were mixed with the resins in a drum blender using a spraying nozzle. MDI was added at 4% and 6% and UF at 8% and 12%. Mats were manually pre-pressed before being hot-pressed at 200°C and 3.2 MPa for 100 s to a design density of 600 kg/m^3, which is a conventional density in furniture applications. Amongst the three raw materials used, little differences were found, even though cup-plant-based boards yield slightly better results. In contrast, the type and quantity of binder played a more decisive role. The most favourable results were obtained with MDI of 6%. Although the resulting boards fulfilled the mechanical requirements for EN 312 P1 class (use in dry conditions), their performance (measured in terms of MOR, MOE, IB, thickness swelling and water absorption) was inferior to that of conventional wood particle boards.

Bektas *et al.* (2004) developed three-layer particle boards from sunflower stalks (*Helianthus annuus*) and poplar wood (*Populus alba*). The ratio of particles from wood or sunflower was 100%, 75%, 50% and 25%. The mixtures of aggregates, sieved at 1.5 mm for the middle layer and 0.8 mm for the surface layer, were bonded with UF (9% for the middle layer and 11% for the surface layer) and a catalyst (1% of ammonium chloride) and hot-pressed (24–26 MPa and 150°C during 7 min) to form particle boards of an end density of 700 kg/m^3. The moisture-related properties (thickness swelling and water absorption), mechanical properties (internal bond, modulus of elasticity and MOR) and screw-holding capacity of the panels were analysed. All the resulting particle boards fulfilled the requirements established in EN 312, for general-purpose use. However, the performance of all the boards incorporating sunflower stalks was lower than that of the 100% poplar wood specimens. The composite made with sunflower stalks only showed the worst performance.

Balducci *et al.* (2008) selected different vegetal-pith-rich parts of crop plants, such as sunflower, topinambur, miscanthus and corn stalks and hemp shives, aiming at the production of lightweight particle boards. One-layer and three-layer particle boards, bonded with 6% pMDI and UF resins, were characterised in terms of mechanical- and moisture-related properties. Particle boards made from wood served as reference. The vegetal materials were cut and hammermilled to produce aggregates. The pith and the bark parts were used together. The typical size of the particles was not mentioned; however, the authors report important differences in shape and density of the resulting particles. The aggregates were blended with the resin and pressed to a target density of 400 or 600 kg/m^3. It was found that density was the main drawing factor affecting the investigated properties. Lightweight boards failed to meet the requirements of P2 applications (EN 312, board for interior use—including furniture—under dry conditions), unlike most of the boards ranging 600 kg/m^3, which did comply with such requirements. For similar densities and formulations, pMDI-bonded boards yield better results. No important differences were found between one-layer and three-layer particle boards in terms of their mechanical properties. Under the same conditions, topinambur boards had higher IB than the rest of the materials, whilst corn stalks showed the lowest IB.

3.10.4.3 Concretes and blocks

A further possible use of vegetal pith in buildings is its utilisation to lighten the weight of plaster mixtures. Cement, lime, gypsum and clay matrices are the most commonly used matrices. The poor compatibility between cement and lignocellulosic materials is well established, and considerable efforts have been made for decades aiming to overcome this problem. Mainly, two different strategies have been explored: the pretreatment of the lignocellulosic materials and the modification of the cement matrix (Claramunt, 2011). However, in order to avoid this problem, cement tends to be replaced by other products, such as lime, in bio-based mixtures (Magniont, 2010). In particular, hemp-lime products, also known as *hempcretes*, have been issued of an extensive research during the last decades (Evrard, 2008; Glé, Gourdon and Arnaud, 2011; Laurent and Gourlay, 2012; Shea *et al.*, 2012; Collet *et al.*, 2013), which resulted in a wide range of products having reached the market during the last years. Tradical Hempcrete, Hemp Eco Systems, The Limecrete Company or Chanvribloc are some examples of the companies currently commercialising hemp-lime products. Lime has been reported to have good compatibility with bio-based materials in terms of a good fibre-matrix interface and matching hygroscopic performance. Moreover, it protects the bio-based materials from biotic degradation.

Diatta *et al.* (2011) investigated the effect of substituting 0.5%–3% of the sand of a cement mortar by typha particles. As expected, the thermal conductivity decreased linearly with the amount of vegetal-pith material, whilst the flexural strength decreased. Pinto *et al.* (2012) developed a lightweight concrete using granulated corn cob as an aggregate. The density, the compressive strength and the thermal insulation properties of a corn-cob concrete were experimentally quantified. The material showed acceptable physical and mechanical properties for its use as a nonload-bearing lightweight concrete. Its density and its thermal performance were comparable with those of expanded clay concrete. However, its compression strength was lower. More recently, Binici *et al.* (2016) produced water-resistant panels using variable mixtures of gypsum and cement, to which was added NaOH and aluminium dust. The panels were lightened with 60% (wt%) grinded corn cobs. The final products had a thermal conductivity between 0.2 and 0.1 W/mK.

Magniont (2010) proposed the use of sunflower pith aggregates for obtaining self-supporting lightweight blocks. The vegetal aggregates were mixed in portions of 1%, 2% and 3% with a mortar binder composed by metakaolin and natural hydraulic lime in equal proportion and activated with 1% glycerol carbonate and 0.25% ethoxylated sorbitan monolaurate. The authors compared mixtures incorporating hemp hurds and mixtures with sunflower pith. It was found that the latter yield better results, which was attributed to the lower density (10 times lower) and lower hygroscopicity of sunflower pith in comparison with hemp hurds. Both aspects helped to maintain the water ratio in the mixture low, resulting in faster drying and higher compaction. Sunflower-pith-based composites had a density between 948 and 750 kg/m^3 and an accessible porosity between 48.3 and 66.9%, reaching a mechanical strength of about 4 MPa at 49 days and a thermal conductivity of 0.133 W/mK. The capillary absorption of these materials was similar or even lower than that of the binder

alone. These were considered acceptable values for their application in buildings. Samples were produced on an industrial scale in a process consisting on compaction by vibration and immediate demoulding, and it was assumed possible improvements due to future optimisation of the formulations and manufacturing process. The main drawback pointed out by the authors was the high sensitivity of sunflower pith to continuous moistening/drying cycles, which may compromise the service lifespan of the composites.

Nozahic *et al.* (2012) conducted a similar research comparing two different concretes, incorporating 5.5% (wt%) of hemp hurds or ground sunflower stalks. A third formulation without vegetal materials was used for the comparison. The binder elaborated was based on trachytic pumice coarse sand activated with hydrated calcic lime. The water absorption of the two aggregates was analysed for its influence on the curing process and the thermal and acoustic properties of the concretes. The two aggregates showed high levels of water absorption and retention capacity, which was attributed to their high porosity and internal structuring. During the first minutes, the behaviour of the two materials was similar. However, after 30 min, the water absorbed by sunflower particles was higher. This was attributed to the alveolar and closed structure of the vegetal pith, which is abundant (about 80%) in sunflower stalks.

3.10.5 Conclusions

Pith is a porous low-density spongy tissue, with a microstructure that makes it interesting for certain building applications. There are many plants, all around the world, that contain pith into their stalks, leaves and other parts. It is therefore an available renewable resource. Some characteristics of pith depend on the type of plant from which it comes. Aquatic plants, such as typha or totora, present a structure (aerenchyma) even more spongy than the parenchyma that constitutes, for example, sorghum or corn pith.

Many examples of successful application in buildings can be found in literature. Proposals for thermal insulation solutions include insulation panels made with pieces of whole stems and panels formed with previously crushed and screened pith. Different source of pith has been used for these experimental insulation panels, such as corn, sunflower, typha and totora. In some cases, binderless boards were developed, whilst in others both inorganic and organic binders were used. Low thermal conductivities, in the range of 0.04–0.06 W/mK, were obtained. The examples found in literature are limited to products in the form of insulation boards; further research is needed on the use of vegetal pith in blown or sprayed insulation systems, which would allow to enlarge the possible applications of vegetal pith. Particle boards and lighten agents in mortars and plasters are other possible applications. Promising results have been obtained up to date. Moreover, vegetal pith might be used in other industries as a substitute to organic foams, such as packaging or automotive industry. The potential applications of this material are still to be established, and further research and industrial efforts are needed in order to develop vegetal-pith-based products that can reach the mainstream market.

References

Abdou, A., Budaiwi, I., 2013. The variation of thermal conductivity of fibrous insulation materials under different levels of moisture content. Constr. Build. Mater. 43, 533–544. http://dx.doi.org/10.1016/j.conbuildmat.2013.02.058.

Abdul Khalil, H.P.S., Bhat, I.U.H., Jawaid, M., Zaidon, A., Hermawan, D., Hadi, Y.S., 2012. Bamboo fibre reinforced biocomposites: a review. Mater. Des. 42, 353–368.

Aeroc, 2016. http://www.aeroc.eu/index.php?lang=eng. (Accessed 24.03.2016).

Ahmad, M., Kamke, F.A., 2005. Analysis of Calcutta bamboo for structural composite materials: physical and mechanical properties. Wood Sci. Technol. 39, 448–459.

Alberts, B., Johnson, A., Lewis, J., Raff, M., Roberts, K., Walter, P., 2010. Molecular Biology of the Cell, third ed. Garland Science, New York. ISBN: 978-0-8153-4129-1.

Al-Homoud, D.M.S., 2005. Performance characteristics and practical applications of common building thermal insulation materials. Build. Environ. 40, 353–366. http://dx.doi.org/10.1016/j.buildenv.2004.05.013.

Amada, S., Ichikawa, Y., Munakata, T., Nagase, Y., Shimuzu, H., 1997. Fibre texture and mechanical graded structure of bamboo. Compos. Part B 28, 13–20.

Amino, Y., 2005. Bamboo-precocious wood composite beams: bending capacity for long-term loading. J. Bamboo Rattan 4 (1), 55–70.

Anonymous, 1997. Methodenhandbuch Band III. Die Chemische Analyse von Futtermitteln, third ed. Verein Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten, Darmstadt.

Anthony, P.A., 1999. The macrofungi and decay of roofs thatched with water reed, Phragmites australis. Mycol. Res. 103, 1346–1352.

Aro, R., Hallikma, E., Kalman, M., Rausberg, V., 1981. Tehnikaleksikon. Valgus, Tallinn, 656 p.

Asdrubali, F., 2006. Survey on the acoustical properties of new sustainable materials for noise control. In: Proceedings of Euronoise. Presented at the Euronoise, Tampere, Finland.

Asdrubali, F., D'Alessandro, F., Schiavoni, S., 2015. A review of unconventional sustainable building insulation materials. Sustain. Mater. Technol. 4, 1–17.

Aslan, M., Sørensen B.F., Madsen, B., 2012. Characterisation of flax fibres and flax fibre composites. Being cellulose based sources of materials (PhD Thesis). DTU Wind Energy (DTU Wind Energy E; No. 0005), 52–89.

Aza Medina, L.C., 2016. La totora como material de aislamiento térmico: propiedades y potencialidades (Master's thesis). Universitat Politènica de Catalunya.

Bajwa, D.S., Sitz, E.D., Bajwa, S.G., Barnik, A.R., 2015. Evaluation of Cattail (*Typha* spp.) for Manufacturing Composite Panels. Ind. Crops Products 75, 195–199.

Balducci, F., Harper, C., Meinlschmidt, P., Dix, B., Sanasi, A., 2008. Development of innovative particleboard panels. Drvna Ind. 59 (3), 131–136.

Bansal, A.K., Zoolagud, S.S., 2002. Bamboo composites: material of the future. J. Bamboo Rattan 1 (2), 119–130.

Barbu, M.C., Réh, R., Dönmez-Cavdar, A., 2014. Lignocellulosic composites. In: Aguilera, A., Davim, P. (Eds.), Research Developments in Wood Engineering and Technology. vol. 8. ISI Global, Hershey, PA, pp. 281–319 (Chapter 8).

Bektas, I., Guler, C., Kalaycioglu, H., Menegeloglu, F., Nacar, M., 2004. The manufacture of particleboards using sunflower stalks (*Helianthus annuus* l.) and poplar wood (*Populus alba* L.). Compos. Mater. 39 (5), 467–473.

Bektaş, İ., Güler, C., Kalaycıoğlu, H., Mengeloğlu, F., Nacar, M., 2005. The manufacture of particleboards using sunflower stalks (*Heliantus annuus* L.) and poplar wood (*Populus alba* L.). J. Compos. Mater. 39 (5), 467–473.

Berge, B., 2000. The Ecology of Building Materials, second ed. Elsevier, Amsterdam, the Netherlands, 453 p.
Berge, B., 2007. Ecology of Building Materials. Routledge, Abingdon, UK.
Billa, E., Koullas, D.P., Monties, B., Koukios, E.G., 1997. Structure and composition of sweet sorghum stalk components. Ind. Crop. Prod. 6 (3), 297–302.
Binici, H., Aksogan, O., Demirhan, C., 2016. Mechanical, thermal and acoustical characterizations of an insulation composite made of bio-based materials. Sustain. Cities Soc. 20, 17–26.
Bledzki, A.K., Sperber, V.E., Faruk, O., 2002. Natural and wood fibre reinforcement in polymers. Shawbury, Rapra Technology, Rapra Rev. Rep. 13 (8), Report 152, 1–147.
Blout, E.R., Stahman, M.A., 1962. Polyamino Acids, Polypeptides and Proteins. Univ. Wis. Press, Wisconsin, USA, p. 275.
Bolat, M., 2005. Use of biomass sources for energy in Turkey and a view to biomass potential. Biomass Bioenergy 29, 32–41.
Bonès, R.M., Sikorski, J., 1967. The histological structure of wool fibres and their plasticity. J. Text. Inst. 58, 521–532. http://dx.doi.org/10.1080/00405006708659949.
Bos, H.L., 2004. Flax, a prehistoric crop with modern applications. In: The Potential of Flax Fibres as Reinforcement for Composite Materials. Technische Universiteit Eindhoven, proefschrift, Eindhoven, pp. 11–21 (Chapter 2).
Bradbury, J.H., 1974. The structure and chemistry of keratin fibers. In: Advances in Protein Chemistry. Academic Press, Cambridge, MA, pp. 111–200.
Bradbury, J., Chapman, G., 1964. The chemical composition of wool I. The separation and microscopic characterization of components produced. Aust. J. Biol. Sci. 17, 960–972.
Bradbury, J., Chapman, G., King, N., 1965. The chemical composition of wool II. Analysis of the major histological components produced by ultrasonic disintegration. Aust. J. Biol. Sci. 18, 353–364.
Braun, R.C., Wilson, M.J.G., 1970. The removal of atmospheric sulphur by building stones. Atmos. Environ. 4, 371–378. http://dx.doi.org/10.1016/0004-6981(70)90082-X.
BRE Group: Green Guide to Specification [WWW Document], 2016. https://www.bre.co.uk/greenguide/. (Accessed 04.02.16).
Brischke, C., Hanske, M., 2016. Durability of untreated and thermally modified reed (Phragmites australis) against brown, white and soft rot causing fungi. Ind. Crop. Prod. 91, 49–55.
British Standards, BS 4046, 1991. Specification for Compressed Straw Building Slabs. BSI, London.
Brown, S.K., Sim, M.R., Abramson, M.J., Gray, C.N., 1994. Concentrations of volatile organic compounds in indoor air—a review. Indoor Air 4, 123–134. http://dx.doi.org/10.1111/j.1600-0668.1994.t01-2-00007.x.
Carfrae, J., 2011. The moisture performance of straw bale construction in a temperate maritime climate (PhD Thesis). University of Plymouth, Plymouth.
Carus, M., Karst, S., Kauffmann, A., Hobson, J., Bertucelli, S., 2013. The European hemp industry: cultivation, processing and applications for fibers, shivs and seeds. European Industrial Hemp Association, Report, pp. 1–9.
CEN, 2009. EN 13501-1:2009. Fire Classification of Construction Products and Building Elements—Part 1: Classification Using Test Data from Reaction-to-Fire Tests. European Standard. European Committee for Standardization, Brussels, Belgium.
Chafei, S., Khadraoui, F., Boutouil, M., Gomina, M., 2015. Effect of flax fibers treatments on the rheological properties of cement mortar incorporating this reinforcement on the mechanical strengths of the cementitious composites. Constr. Build. Mater. 79, 229–235.
Chapman, G.V., Bradbury, J.H., 1968. The chemical composition of wool VII. Separation and analysis of orthocortex and paracortex. Arch. Biochem. Biophys. 127, 157–163. http://dx.doi.org/10.1016/0003-9861(68)90212-9.

Charlet, K., Jernot, J.P., Moussa, G., Baley, C., Bizet, L., Brear, J., 2007. Morphology and mechanical behaviour of a natural composite: the flax fiber. In: 16th International Conference on Composite Materials, Kyoto, Japan.

Cheng, W.F., Lee, Y.Y., Ng, C.F., 2003. Waste rubber for noise reduction. In: 한국소음진동공학회 국제학술발표논문집 (Inter-Noise and Noise-Con Congress and Conference Proceedings, InterNoise03, Seogwipo KOREA), 2003 년 1 호, pp. 3413–3417.

Chung, K.F., Yu, W.K., 2002. Mechanical properties of structural bamboo for bamboo scaffoldings. Eng. Struct. 24, 429–442.

Claramunt, J., 2011. Utilització de fibres vegetals per a l'elaboració de morters de ciment d'altes prestacions (SHCC) (PhD Thesis). Universitat Politècnica de Catalunya.

Clemons, C., 2002. Wood-plastic composites in the United States: the interfacing of two industries. For. Prod. J. 52 (6), 10–18.

Collet, F., Chamoin, J., Pretot, S., 2013. Comparison of the hygric behaviour of three hemp concretes. Energy Build. 62, 294–303.

CSIRO, 2011. Wool Fibre Structure—CSIROpedia [WWW Document]. CSIROpedia. http://www.csiropedia.csiro.au/display/CSIROpedia/Wool+fibre+structure. (Accessed 13.11.13).

Cundiff, J.S., Worley, J.W., 1992. Chopping parameters for separation of sweet sorghum pith and rind-leaf. Bioresour. Technol. 39 (3), 263–269.

Curling, S.F., Loxton, C., Ormondroyd, G.A., 2012. A rapid method for investigating the absorption of formaldehyde from air by wool. J. Mater. Sci. 47, 3248–3251. http://dx.doi.org/10.1007/s10853-011-6163-7.

Dai, D., 2012. Hemp nanocellulose: fabrication, characterisation and application (A thesis Submitted for the Degree of Doctor of Philosophy). School of Engineering and Design, Brunel University, pp. 1–231.

D'Alessandro, F., Pispola, G., et al., 2005. Sound absorption properties of sustainable fibrous materials in an enhanced reverberation room. In: Proc. Inter-Noise. Rio de Janeiro.

Damman, A.W.H., French, T.W., 1987. The Ecology of Peat Bogs of the Glaciated Northeastern United States: A Community Profile. US Department of the Interior Fish and Wild Life Service Research and Development National Wetlands Research Center, Washington, DC. 100 p.

Dammer, L., Carus, M., Raschka, A., Scholz, L., 2013. Market developments of and opportunities for biobased products and chemicals. Report 52202. Nova-Institute for Ecology and Innovation, pp. 1–69.

Das, M., Chakraborty, D., 2006a. Influence of alkali treatment on the fine structure and morphology of bamboo fibers. J. Appl. Polym. Sci. 102, 5050–5056.

Das, M., Chakraborty, D., 2006b. Influence of mercerization on the dynamic mechanical properties of bamboo, a natural lignocellulosic composite. Ind. Eng. Chem. Res. 45, 6489–6492.

Das, M., Chakraborty, D., 2008. Evaluation of improvement of physical and mechanical properties of bamboo fibers due to alkali treatment. J. Appl. Polym. Sci. 107, 522–527.

Das, M., Pal, A., Chakraborty, D., 2006. Effects of mercerization of bamboo strips on mechanical properties of unidirectional bamboo-novolac composites. J. Appl. Polym. Sci. 100, 238–244.

De Long, J., 1923. Insulating material. US 1442325 A. Jan 16.

Desarnaulds, V., Costanzo, E., Carvalho, A., Arlaud, B., 2005. Sustainability of acoustic materials and acoustic characterization of sustainable materials. In: Proceedings of the 12th International Congress on Sound and Vibration, 11–14 July 2005. Lisbon, Portugal.

Deshpande, A.P., Rao, M.B., Rao, C.L., 2000. Extraction of bamboo fibers and their use as reinforcement in polymeric composites. J. Appl. Polym. Sci. 76, 83–92.

Diatta, M.T., Gaye, S., Thiam, A., Azilinon, D., 2011. Détermination des propriétés thermophysique et mécanique du *Typha australis*. Cong. SFT, Perpignan, France.

Dix, B., Meinlschmidt, P., Van de Flierdt, A., Thole, V., 2009. Leichte spanplatten für den möbelbau aus rückständen der landwirtschaftlichen production: teil 1: verfügbarkeit der rohstoffe. Holztechnologie 50 (2), 5–10.

Dosdall, R., Hahn, V., Preuss, F., Kreisel, H., Miersch, H., Schauer, F., 2014. Characterization of fungi of the genus mycena isolated from houses thatched with phragmites communis Trin. In northern Germany: enzyme pattern and reed decay. Int. Biodeterior. Biodegrad. 96, 174–180.

Dowling, A., Mathias, J.A., 2007. Experimental determination of the insulating ability of corn by-products. J. Sustainable Agric. 30 (2), 15–27.

Ecoconstruct, 2014. Ecoconstruct 3D-Printing of Small Buildings Based on a Novel Eco-Sustainable Construction Material. Elva E.P.T AS Eesti Turbauuringute Keskus OÜ, Tartu. 36 p.

Ecoinvent [WWW Document], 2016. http://www.ecoinvent.org/. (Accessed 03.02.16).

EEA, 2013. Air quality in Europe. 2013 Report (No. 9/2013). European Environment Agency, København.

Eesti Turbaliit, 2016. Turvas. http://www.turbaliit.ee/turvas/. (Accessed 24.03.2016).

Elmendorf, A., 1929. Insulating building material and method of making the same. U.S. Patent No. 1,741,760, U.S. Patent and Trademark Office, Washington, DC.

EPA, 1991. Formaldehyde (CASRN 50-00-0) [WWW Document]. http://www.epa.gov/iris/subst/0419.htm. (Accessed 10.14.13).

Eriksen Hagen Stenberg, M., Laursen Back, T., Rode, C., Hansen, K.K., 2008. Hygrothermal properties and performance of sea grass insulation. In: The Nordic Journal of Building Physics/The 8th symposium on Building Physics in the Nordic Countries, June 16-18th. Div. of Building Technology/Department of Civil and Architectural Engineering/Royal Institute of Technology, Stockholm. 8 p. http://web.byv.kth.se/bphys/copenhagen/ (15.09.2016).

European Parliament and Council, 2008. Regulation (EC) No. 1272/2008 of the European Parliament and of the Council of 16 December 2008 on Classification, Labelling and Packaging of Substances and Mixtures, Amending and Repealing Directives 67/548/EEC and 1999/45/EC, and Amending Regulation (EC) No 1907/2006. (No. 1272/2008/EC).

Evans, D.J., Leeder, J.D., Rippon, J.A., Rivett, D.E., 1985. Separation and analysis of the surface lipids of the wool fiber. In: 7th International Wool Textile Research Conference, Tokyo. pp. 135–142.

Evrard, A., 2008. Transient hygrothermal behaviour of lime-hemp materials. PhD Thesis, Universite Catholique de Louvain.

Fairbairn, A.S., Reid, D.D., 1958. Air pollution and other local factors in respiratory disease. Br. J. Prev. Soc. Med. 12, 94–103.

Febrianto, F., Gumilang, A., Maulana, S., Busyra, I., Purwaningsih, A., 2014. Natural durability of five bamboo species against termites and powder post beetle. J. Ilmu Teknol. Kayu Tropis 12 (2), 146–156.

Fei, B., Gao, Z., Wang, J., Liu, Z., 2016. Biological, anatomical, and chemical characteristics of bamboo. In: Secondary Xylem Biology. Elsevier, Amsterdam, the Netherlands, pp. 283–306.

Fisk, W.J., Rosenfeld, A.H., 1997. Estimates of improved productivity and health from better indoor environments. Indoor Air 7, 158–172. http://dx.doi.org/10.1111/j.1600-0668.1997.t01-1-00002.x.

Folk, J.E., 1977. The epsilon-(gamma-glutamyl) lysine crosslink and the catalytic role of transglutaminase. Adv. Protein Chem. 31, 1–120.

Franchi, M., Carrer, P., Kotzias, D., Rameckers, E.M.A.L., Seppänen, O., Van Bronswijk, J.E.M.H., Viegi, G., Gilder, J.A., Valovirta, E., 2006. Working towards healthy air in dwellings in Europe. Allergy 61, 864–868. http://dx.doi.org/10.1111/j.1398-9995.2006.01106.x.

Georgiev, G., Theuerkorn, W., Krus, M., Kilian, R., Grosskinsky, T., 2014. The potential role of cattail-reinforced clay plaster in sustainable building. Mires Peat 13, 1–13.
Glé, P., Gourdon, E., Arnaud, L., 2011. Acoustical properties of materials made of vegetable particles with several scales of porosity. Appl. Acoust. 72 (5), 249–259.
González, C., Gutiérrez, J., 2005. Structural performance of bamboo 'bahareque' walls under cyclic load. J. Bamboo Rattan 4 (4), 353–368.
Goodhew, S., Carfrae, J., De Wilde, P., 2010. Briefing: challenges related to straw bale construction. Proc. Inter. Civ. Eng.-Eng. Sustain. 163 (4), 185–189.
Gramitherm, 2016. Products/Technical Specifications. Clean Insulating Technologies SA, Lausanne. http://gramitherm.ch/?page_id=443#tab-id-2. (Accessed 16.09.2016).
Gutu, T., 2013. A study on the mechanical strength properties of bamboo to enhance its diversification on its utilization. Int. J. Innov. Technol. Explor. Eng. 2, 314–319.
Habibi, M.K., Tam, L., Lau, D., Lu, Y., 2016. Viscoelastic damping behaviour of structural bamboo material and its microstructural origins. Mech. Mater. 97, 184–198.
Hague, J.R.B., McLauchlin, A., Quinney, R., 1998. Agri-materials for panel products: a technical assessment of their viability. In: Proceedings of the 32nd Washington State University International Particleboard/Composites Materials Symposium, Pullman, WA. pp. 151–159.
Harper, S., Lynch, J., 1981. The chemical components and decomposition of wheat straw leaves, internodes and nodes. 32 (11), 1057–1062.
Haslam, S.M., 1989. Early decay of phragmites Australis. Aquat. Bot. 35, 129–132.
Hax, S., et al., 2000. Residues utilization from shoes industry in the acoustic insulation in buildings. In: Proc. of Internoise, Nice, France.
Hedlin, C., 1967. Sorption isotherms for five different types of wheat straw. Can. Agric. Eng. 9 (1), 37–42.
Hill, C.A.S., Norton, A.J., Newman, G., 2010. The water vapour sorption properties of Sitka spruce determined using a dynamic vapour sorption apparatus. Wood Sci. Technol. 44 (3), 497–514.
Hinde, J.J., 1927. Process of manufacturing insulating and plaster board from cornstalks. US 1623184.
Hiziroglu, S., Bauchonkol, P., Fueangvivat, V., Soontonbura, W., Jarusombruti, S., 2007. Selected properties of medium density fiberboard (MDF) panels made from bamboo and rice straw. For. Prod. J. 57 (6), 46–50.
Hofmann, K., Kreisel, H., Kordon, K., Preuss, F., Kües, U., Schauer, F., 2016. The key role of lignin decomposing fungi in the decay of roofs thatched with water reed. Mycol. Prog. 15, 1–7. http://dx.doi.org/10.1007/s11557-016-1181-0.
Holzmann, G., Wangelin, M., Bruns, R., 2012. Natürliche und pflanzliche Baustoffe. Springer, Berlin.
Hooper, F.E., 1930. Composition and structure of the cornstalk as related to its industrial utilization (Thesis dissertation). Iowa State University.
Hunter, I.R., 2003. Bamboo resources, uses and trade: the future? J. Bamboo Rattan 2 (4), 319–326.
Jain, S., Kumar, R., Jindal, U.C., 1992. Mechanical behaviour of bamboo and bamboo composite. J. Matter Sci. 27, 4598–4604.
Jain, S., Kumar, R., Jindal, U.C., 1993. Development and fracture mechanism of the bamboo/polyester resin composite. J. Matter Sci. Lett. 12, 558–560.
Jindal, U.C., 1986. Development and testing of bamboo fibres reinforced plastic composites. J. Compos. Matter 20, 19–29.
Jones, B., 2009. Building With Straw Bales: A Practical Guide for the UK and Ireland. Green Books, Cambridge, UK, 160 p.

Joshi, S.V., Drzal, L.T., Mohanty, A.K., Arora, S., 2004. Are natural fiber composites environmentally superior to glass fiber reinforced composites? Compos. Part Appl. Sci. Manuf. 35, 371–376. http://dx.doi.org/10.1016/j.compositesa.2003.09.016. AIChE 2002.

Jürgenson, L., 1942a. Elamu Soojapidavus, Drittes Reich Tartu Eesti Kirjastus, Tartu. 248 p.

Jürgenson, L., 1942b. Elamu soojapidavus, Drittes Reich Tartu Eesti Kirjastus, Tartu. 248 p. 43, 46–47, 114–115, 120–121.

Kaack, K., Schwarz, K.U., Brander, P.E., 2003. Variation in morphology, anatomy and chemistry of stems of Miscanthus genotypes differing in mechanical properties. Ind. Crop. Prod. 17 (2), 131–142.

Kalia, S., Kaith, B.S., Kaur, I., 2009. Pretreatments of natural fibers and their application as reinforcing material in polymer composites—a review. Polym. Eng. Sci. 49 (7), 1253–1272.

Kehrer, M., Kunzel, H.M., Sedlbauer, K., 2003. Ecological insulation materials—does sorption affect their insulation performance? J. Therm. Envel. Build. Sci. 26, 207–212.

Kermani, A., 2006. Performance of structural insulated panels. Proc. Inst. Civ. Eng. Struct. Build. 159 (1), 13–19.

Khalil, H.P.S.A., Bhat, I.U.H., Jawaid, M., Zaidon, A., Hermawan, D., Hadi, Y.S., 2012. Bamboo fibre reinforced biocomposites: a review. Mater. Des. 42, 353–368.

Khazma, M., Goullieux, A., Dheilly, R.M., Quéneudec, M., 2014. Optimization of flax shive-cementitious composites: impact of different aggregate treatments using linseed oil. Ind. Crop. Prod. 61, 442–452.

King, B., 1996. Buildings of Earth and Straw. Ecological Design Press, Sausalito, CA. 169 p.

King, B., 2006. Design of Straw Bale Buildings. Green Building Press, San Rafael, CA. 259 p.

Kirby, J.J.H., Rayner, A.D.M., 1989. The deterioration of thatched roofs. Int. Biodeterior. 25, 21–26.

Klímek, P., Meinlschmidt, P., Wimmer, R., Plinke, B., Schirp, A., 2016. Using sunflower (Helianthus annuus L.), topinambour (Helianthus tuberosus L.) and cup-plant (Silphium perfoliatum L.) stalks as alternative raw materials for particleboards. Ind. Crop. Prod. 92, 157–164.

Kollmann, F.F.P., Kuenzi, E.W., Stamm, A.J., 1975. Flax shives. In: Principles of Wood Science and Technology. II. Wood Base Materials. Springer-Verlag, London, UK, pp. 322–323 (Chapter 5).

Konsa, K., Pilt, K., 2012. Hoonete biokahjustused. AS Atlex, Tartu. 165 p.

Konto Oy, 2015. http://www.konto.fi/en/products/insulation. (Accessed 14.01.2015).

Korjenic, A., Bednar, T., 2011. Developing a model for fibrous building materials. Energ. Buildings 43, 3189–3199. http://dx.doi.org/10.1016/j.enbuild.2011.08.017.

Korjenic, A., Bednar, T., 2012. An analytical solution of a moisture transfer problem for coupled room and building component. Energ. Buildings 47, 254–259. http://dx.doi.org/10.1016/j.enbuild.2011.11.045.

Korjenic, A., Teblick, H., Bednar, T., 2010. Increasing the indoor humidity levels in buildings with ventilation systems: simulation aided design in case of passive houses. Build. Simul. 3, 295–310. http://dx.doi.org/10.1007/s12273-010-0015-2.

Korjenic, A., Petranek, V., Zach, J., Hroudova, J., 2011. Development and performance evaluation of natural thermal-insulation materials composed of renewable resources. Energ. Buildings 43 (9), 2518–2523.

Krus, M., Werner, T., Großkinsky, T., Georgiev, G., 2015. A new load-bearing insulation material made of cattail. In: First International Conference on Bio-Based Building Materials, ICBBM, Jun 2015, Clermont Ferrand, France.

Kulkarni, V., Bradbury, J., 1974. The chemical composition of wool XII. Further studies on cortical cells and macrofibrils. Aust. J. Biol. Sci. 27, 383–396.

Kymäläinen, H.R., Sjöberg, A.M., 2008. Flax and hemp fibres as raw materials for thermal insulations. Build. Environ. 43 (7), 1261–1269.

Lakkard, S.C., Patel, J.M., 1980. Mechanical properties of bamboo, a natural composite. Fibre Sci. Technol. 81 (14), 319–322.
Lamarche, G., 1921. Fraiches en ete, chaudes en hiver, les maisons de paille sont avant tout economiques. La Science et la Vie 56, 481–486.
Lappalainen, E., 1996. Global Peat Resources. International Peat Society, Jyskä. 359 p.
Laurent, A., Gourlay, E., 2012. Experimental study of parameters influencing mechanical properties of hemp concretes. Constr. Build. Mater. 28 (1), 50–56.
Lawrence, M., 2015. Reducing the environmental impact of construction by using renewable materials. J. Renew. Mater. 3 (3), 163–174.
Lawrence, M., Heath, A., Walker, P., 2009. Determining moisture levels in straw bale construction. Constr. Build. Mater. 23, 2763–2768.
Lee, S., Shupe, T.F., Hse, C.Y., 2006. Mechanical and physical properties of agro-based fibreboard. Holz Roh Werkst. 64 (1), 74–79.
Lee, D., Owens, V., Boe, A., Jeranyama, P., 2007. Composition of herbaceous biomass feedstocks. Report for the Sun Grant Initiative, South Dakota State University, Brookings, SD, USA.
Li, Y., Holcombe, B.V., Apcar, F., 1992. Moisture buffering behavior of hygroscopic fabric during wear. Text. Res. J. 62, 619–627. http://dx.doi.org/10.1177/004051759206201101.
Li, S.H., Fu, S.Y., Zhou, B.L., Zeng, Q.Y., Bao, X.R., 1994. Reformed bamboo and reformed bamboo/aluminium composite. J. Mater. Sci. 29, 5990–5996.
Li, X., Shupe, T.F., Hse, C.Y., 2004. Physical and mechanical properties of medium density fibreboards from bamboo and tallow wood fibres. J. Bamboo Rattan 3 (4), 383–392.
Li, X., Lei, B., Li, Z., Huang, L., Tan, S., Cai, X., 2014a. The utilization of bamboo charcoal enhances wood plastic composites with excellent mechanical and thermal properties. Mater. Des. 53, 419–424.
Li, X., Wang, S., Du, G., Wu, Z., Gong, Y., 2014b. Manufacturing particleboard using hemp shiv and wood particles with low free formaldehyde emission urea-formaldehyde resin. For. Prod. J. 64 (5–6), 187–191.
Liese, W., 1987. Research on bamboo. Wood Sci. Technol. 21, 189–209.
Liese, W., 1996. Structural research on bamboo and rattan for their wider utilisation. J. Bamboo Rattan 15 (2), 1–14.
Long, L., Nany, Z., Chen, K., 2015. Analysis of the hollow structure with functionally gradient materials of moso bamboo. J. Wood Sci. 61, 569–577.
Low, I.M., Che, Z.Y., Latella, B.A., Sim, K.S., 2006. Mechanical and fracture properties of bamboo. Key Eng. Mater. 312, 15–20.
Luamkanchanaphan, T., Chotikaprakhan, S., Jarusombati, S., 2012. A study of physical, mechanical and thermal properties for thermal insulation from narrow-leaved cattail fibers. APCBEE Procedia 1, 46–52.
Lyon, R.E., Walters, R.N., 2004. Pyrolysis combustion flow calorimetry. J. Anal. Appl. Pyrolysis 71 (1), 27–46.
Ma, X., Wang, G., Zehui, J., Xian, Y., Li, H., 2014. Comparison of bending creep behaviour of bamboo-based composites manufactured by two types of stacking sequences. Bioresources 9 (3), 5461–5472.
Magniont, C., 2010. Contribution à la formulation et à la caractérisation d'un écomatériau de construction à base d'agroressources (Doctoral disertation). Université de Toulouse.
Mansour, E., Loxton, C., Elias, R.M., Ormondroyd, G.A., 2014. Assessment of health implications related to processing and use of natural wool insulation products. Environ. Int. 73, 402–412. http://dx.doi.org/10.1016/j.envint.2014.08.004.

Mansour, E., Curling, S., Stéphan, A., Ormondroyd, G., 2016. Absorption of volatile organic compounds by different wool types. Green Mater. 4 (1), 1–7.
Marchant, G.E., Amen, M.A., Bullock, C.H., Carter, C.M., Johnson, K.A., Reynolds, J.W., Connelly, F.R., Crane, A.E., 2002. A synthetic vitreous fiber (SVF) occupational exposure database: implementing the SVF health and safety partnership program. Appl. Occup. Environ. Hyg. 17, 276–285. http://dx.doi.org/10.1080/10473220252826583.
Mati-Baouche, N., De Baynast, H., Lebert, A., Sun, S., Lopez-Mingo, C.J.S., Leclaire, P., Michaud, P., 2014. Mechanical, thermal and acoustical characterizations of an insulating bio-based composite made from sunflower stalks particles and chitosan. Ind. Crop. Prod. 58, 244–250.
Maxwell, J.M., Huson, M.G., 2005. Scanning probe microscopy examination of the surface properties of keratin fibres. Micron 36, 127–136. http://dx.doi.org/10.1016/j.micron.2004.10.001.
Meyer, B., Boehme, C., 1997. Formaldehyde emission from solid wood. For. Prod. J. 47, 45–48.
Miljan, M.-J., Miljan, J., 2012. Kohalikud looduslikud ehitusmaterjalid. Soojustusmaterjalide omaduste määramine maaehituse osakonna ehitusfüüsika laboris. EstUnivLifeSc, Tartu. 114 p.
Mohanty, A.K., Misra, M., Drzal, L.T., 2005. Natural Fibres, Biopolymers and Biocomposites. CRC Press, Boca Raton, FL.
Montanarella, L., Jones, R.J.A., Hiederer, R., 2006. The distribution of peatland in Europe. Mires Peat 1. 11 p. http://www.mires-and-peat.net. (Accessed 01.09.2016).
Mortan, W.E., Hearle, L.W., 1975. Physical Properties of Textile Fibers. Heinemann, London.
Müssig, J., Stevens, C., 2010. Industrial Applications of Natural Fibres: Structure, Properties and Technical Applications. John Wiley & Sons, Chichester.
Negri, A.P., Cornell, H.J., Rivett, D.E., 1993. A model for the surface of keratin fibers. Text. Res. J. 63, 109–115. http://dx.doi.org/10.1177/004051759306300207.
Nielsen, G.D., Wolkoff, P., 2010. Cancer effects of formaldehyde: a proposal for an indoor air guideline value. Arch. Toxicol. 84, 423–446. http://dx.doi.org/10.1007/s00204-010-0549-1.
Nikvash, N., Kharazipour, A., Euring, M., 2012. Effects of wheat protein as a biological binder in the manufacture of particleboards using a mixture of canola, hemp, bagasse, and commercial wood. For. Prod. J. 62 (1), 49–57.
Nozahic, V., Amziane, S., Torrent, G., Saïdi, K., De Baynast, H., 2012. Design of green concrete made of plant-derived aggregates and a pumice–lime binder. Cem. Concr. Compos. 34, 231–241.
Obataya, E., Kitin, P., Yamouchi, H., 2007. Bending characteristics of bamboo (Phyllostachys pubescens) with respect to its fiber-foam composite structure. Wood Sci. Technol. 41, 385–400.
Okubo, K., Fujii, T., Yamamoto, Y., 2004. Development of bamboo-based polymer composites and their mechanical properties. Compos. A: Appl. Sci. Manuf. 35, 377–383.
Olorunnisola, A.O., 2005. Dimentional stability of cement-bonded composite boards made from rattan cane particles. J. Bamboo Rattan 4 (2), 173–182.
Olorunnisola, A.O., Pitman, A., Mansfield-William, H., 2005a. Hydration characteristics of cement-bonded composites made from rattan cane and coconut husk. J. Bamboo Rattan 4 (2), 193–201.
Olorunnisola, A.O., Pitman, A., Mansfield-William, H., 2005b. Strength properties and potential uses of rattan-cement composites. J. Bamboo Rattan 4 (4), 343–352.
Orru, M., Orru, H., Tuulik, V.-R., Übner, M., 2007. Eesti turba balneoloogiliste kasutamisvõimaluste uuring (III etapp). Eesti Geoloogiakeskus, rakendusgeoloogia osakond, Tallinn. 25 p.

Osorio, L., Trujillo, E., Vuure, A.W.V., Verpoest, I., 2010. Morphological aspects and mechanical properties of single bamboo fibres and flexural characterization of bamboo/epoxy composites. J. Reinf. Plast. Compos. 30, 396–408.

Otloot, H., Veski, A., 1952. Arhitektuuri ja ehitustehnika alused. Tartu Kommunist, Tartu, 551 p.

Palumbo, M., 2015. Contribution to the development of new bio-based thermal insulation materials made from vegetal pith and natural binders: hygrothermal performance, fire reaction and mould growth resistance (Doctoral dissertation). Universitat Politècnica de Catalunya.

Palumbo, M., Navarro, A., Giraldo, P., Lesar, B., Lacasta, A.M., 2015a. Performance of biobased insulation board from crop by-products and natural gums. In: First International Conference on Bio-Based Building Materials, ICBBM, Jun 2015, Clermont Ferrand, France.

Palumbo, M., Formosa, J., Lacasta, A.M., 2015b. Thermal degradation and fire behaviour of thermal insulation materials based on food crop by-products. Constr. Build. Mater. 79, 34–39.

Palumbo, M., Lacasta, A.M., Holcroft, N., Shea, A., Walker, P., 2016. Determination of hygrothermal parameters of experimental and commercial bio-based insulation materials. Constr. Build. Mater. 124, 269–275.

Papadopoulos, A.M., 2005. State of the art in thermal insulation materials and aims for future developments. Energ. Buildings 37, 77–86. http://dx.doi.org/10.1016/j.enbuild.2004.05.006.

Papadopoulos, A.N., Hague, J.R.B., 2003. The potential for using flax (Linum usitatissimum L.) shiv as a lignocellulosic raw material for particleboard. Ind. Crop. Prod. 17, 143–147.

Patent RU2514973 (C1), 2014. Торфодревесная формовочная смесь для изготовления теплоизоляционных и конструкционно-теплоизоляционных изделий (Peat-wood moulding mixture for making heat insulation and structural–heat insulation articles). Espacenet. https://ee.espacenet.com/publicationDetails/biblio?CC=RU&NR=2514973C1&KC=C1&FT=D&ND=6&date=20140510&DB=&locale=ee_EE. (Accessed 09.09.2016).

Patkowska-Sokola, B., Dobrzański, Z., Osman, K., Bodkowski, R., Zygadlik, K., 2009. The content of chosen chemical elements in wool of sheep of different origins and breeds. Arch. Tierernahr. 52, 410–418.

Patnaik, A., Mvubu, M., Muniyasamy, S., Botha, A., Anandjiwala, R.D., 2015. Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies. Energ. Buildings 92, 161–169. http://dx.doi.org/10.1016/j.enbuild.2015.01.056.

Paulus, P., 2011. Puistesoojustusmaterjalide vajumise dünaamika ja soojusjuhtivus (Dynamic and thermal conductivity of bulk isolation materials) (Master thesis). Estonian University of Life Sciences, 60 p.

Pecenka, R., Furll, C., Idler, C., Grundmann, P., Radosavljevic, L., 2009. Fibre boards and composites from wet preserved hemp. Int. J. Mater. Prod. Technol. 36 (1–4), 208–220.

Pecenka, R., Fürll, C., Gusovius, H.J., 2010. Economic production and processing of agricultural fibre plants for high quality applications in automotive, building and furniture industry. In: Proceedings of CIGR, XVIIth World Congress, CSBE/SCGAB. pp. 1–4. http://www.csbe-scgab.ca/docs/meetings/2010.

Peters, D., Bradbury, J., 1976. The chemical composition of wool XV. The cell membrane complex. Aust. J. Biol. Sci. 29, 43–56.

Pinto, J., Paiva, A., Varum, H., et al., 2011. Corn's cob as a potential ecological thermal insulation material. Energ. Buildings 43 (8), 1985–1990.

Pinto, J., Vieira, B., Pereira, H., et al., 2012. Corn cob lightweight concrete for non-structural applications. Constr. Build. Mater. 34, 346–351.

Pizzutti, J.L., de Oliveira, M.A., Picada, G., 2005. Acoustic potential of calabash residue as sound absorption alternative material. In: INTER-NOISE and NOISE-CON Congress and Conference Proceedings. Institute of Noise Control Engineering. pp. 4451–4456.

PRé Sustainability [WWW Document], 2016. https://www.pre-sustainability.com/. (Accessed 04.02.16).

Preisner, M., Wojtasik, W., Kulma, A., Żuk, M., Szopa, J., 2014. Flax fiber. Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, New Jersey, USA, pp. 1–32.

Püttmann, K., 2011. Der Zustand der Reetdächer. 31 Berichte zur Denkmalpflege, Niedersachsen, pp. 148–151.

Rachchh, N.V., Ujeniya, P.S., Misra, R.K., 2014. Mechanical characterisation of rattan fibre polyester composite. Procedia Mater. Sci. 6, 1396–1404.

Ray, A.K., Das, S.K., Mondal, S., 2004. Microstructural characterization of bamboo. J. Mater. Sci. 39, 1055–1060.

Réh, R., Osvald, A., 1996. Contribution to the fire retardant treatment of flax board panels. Fol. Forest. Polonica 27, 79–83.

Réh, R., Vrtielka, J., 2012. Modification effect of the core layer with addition of shivs for particleboard manufacture. In: Proceedings of the 9th International Conference of the European Industrial Hemp Association (EIHA). Wesseling. http://www.eiha.org/attach/751/Reh_Vrtielka_ EIHA_2012.pdf.

Rogers, G.E., 1959. Electron microscope studies of hair and wool. Ann. N. Y. Acad. Sci. 83, 378–399. http://dx.doi.org/10.1111/j.1749-6632.1960.tb40914.x.

Rogers, G.E., Bawden, C.S., 2008. The protein structure of wool and its relation to physical properties. In: Advances in Wool Technology. Elsevier, Amsterdam, the Netherlands, pp. 10–13.

Salvadó, J., Velásquez, J.A., Ferrando, F., 2003. Binderless fiberboard from steam exploded Miscanthus sinensis: optimization of pressing and pretreatment conditions. Wood Sci. Technol. 37 (3–4), 279–286.

Sawpan, M.A., Pickering, K.L., Fernyhough, A., 2011. Improvement of mechanical performance of industrial hemp fibre reinforced polylactide biocomposites. Compos. A: Appl. Sci. Manuf. 42 (3), 310–319.

Schlossman, M.L., McCarthy, J.P., 1978. Lanolin and its derivatives. J. Am. Oil Chem. Soc. 55, 447–450. http://dx.doi.org/10.1007/BF02911911.

Schmidt, A.C., Jensen, A.A., Clausen, A.U., Kamstrup, O., Postlethwaite, D., 2004. A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Part 1: background, goal and scope, life cycle inventory, impact assessment and interpretation. Int. J. Life Cycle Assess. 9 (1), 53–66.

Schopper, C., Kharazipour, A., Bohn, C., 2009. Production of innovative hemp based three-layered particleboards with reduced raw densities and low formaldehyde emissions. Int. J. Mater. Prod. Technol. 36 (1–4), 358–371.

Secchi, S., 2005. Acoustic and thermal performances of building materials. In: Proc. of the 1st International Workshop on Sustainable Materials for Noise Control, Terni, Italy.

Sedlbauer, K., Hofbauer, W., Krueger, N., Mayer, F., Breuer, K., 2011. Material specific isopleth-systems as valuable tools for the assessment of the durability of building materials against mould infestation—the 'isopleth-traffic light'. In: International conference on Building Materials and Components, Porto, Portugal.

Seema Jain, R.K., Jindal, U.C., 1992. Mechanical behaviour of bamboo and bamboo composite. J. Mater. Sci. 27, 4598–4604.

Selinger, J., Wimmer, R., 2015. A novel low-density sandwich panel made from hemp. In: Horáček, P. (Ed.), Wood 2015: Innovations in Wood Materials and Processes, Brno. pp. 93–94.

Seo, J., Kato, S., Ataka, Y., Chino, S., 2009. Performance test for evaluating the reduction of VOCs in rooms and evaluating the lifetime of sorptive building materials. Build. Environ. 44, 207–215. http://dx.doi.org/10.1016/j.buildenv.2008.02.013.

Shang, L., Zhengjun, S., Liu, X., Jiang, Z., 2015. A novel method for measuring mechanical properties of vascular bundles in moso bamboo. J. Wood Sci. 61, 562–568.

Shea, A., Lawrence, M., Walker, P., 2012. Hygrothermal performance of an experimental hemp-lime building. Constr. Build. Mater. 36, 270–275.

Shea, A., Wall, K., Walker, P., 2013. Evaluation of the thermal performance of an innovative prefabricated natural plant fibre building system. Build. Serv. Eng. Res. Technol. 34 (4), 369–380.

Shin, F.G., Yipp, M.W., 1989. Analysis of the mechanical properties and microstructure of bamboo-epoxy composites. J. Mater. Sci. 24, 3483–3490.

Shurtleff, W., 1933. Method and apparatus for purifying. US Patent 1937483.

Sodagar, B., Rai, D., Jones, B., Wihan, J., Fieldson, R., 2011. The carbon-reduction potential of straw-bale housing. Build. Res. Inf. 39 (1), 51–65.

Soljacic, I., Cunko, R., 1994. Croatian textiles throughout history. Tekstil 43 (11), 584–602.

Speakman, J.B., 1931. The micelle structure of the wool fibre. Proc. R. Soc. Lond. A 132, 167–191.

Stanwix, W., Sparrow, A., 2014. The Hempcrete Book. Designing and Building With Hemp-Lime. Green Books, Totnes, UK. ISBN: 9780857841209.

Stone, A., Massey, A., Theobald, M., Styslinger, M., Kane, D., Kandy, D., avert, E., 2011. Africa's indigenous vegetables. In: World Watch Institute (Eds.), The State of the World. Worldwatch Institute Europe, Copenhagen, Denmark. http://www.worldwatch.org/system/files/NtP-Africa's-Indigenous-Crops.pdf.

Strandberg, M., 2014. Turbakasutuse ökoloogiliselt tasakaalustatud viisidest: II osa Turbakasutuse tehnilistest ja energeetilistest võimalustest. Tallinn. http://www.energiatalgud.ee/img_auth.php/7/76/Strandberg,_M._Turbakasutuse_%C3%B6koloogiliselt_tasakaalustatud_viisidest_-_II.pdf. (Accessed 08.09.16).

Stuart, I.M., Schneider, A.M., Turner, T.R., 1989. Perception of the heat of sorption of wool. Text. Res. J. 59, 324–329. http://dx.doi.org/10.1177/004051758905900603.

Sumardi, I., Ono, K., Suzuki, S., 2007. Effect of board density and layer structure on the mechanical properties of bamboo oriented strandboard. J. Wood Sci. 53 (6), 510–515.

Sun, S., Mathias, J.D., Toussaint, E., Grédiac, M., 2013. Hygrothermal characterization of sunflower stems. Ind. Crop. Prod. 46, 50–59.

Sweeney, O.R., Emley, W.E., 1930. Manufacture of Insulating Board From Cornstalks. vol. 13. US Government Printing Office, Washington, USA.

Swift, J.A., Smith, J.R., 2001. Microscopical investigations on the epicuticle of mammalian keratin fibres. J. Microsc. 204, 203–211. http://dx.doi.org/10.1046/j.1365-2818.2001.00957.x.

Tehnika ja Tootmine, 1980–3. Turbast maja. Perioodika, Tallinn.

Teppand, T., 2015. Using of peat as insulation material. Properties and technologies. Poster, Estonian University of Life Sciences, 1 p.

Theis, M., Grohe, B., 2002. Biodegradable lightweight construction boards based on tannin/hexamine bonded hemp shaves. Holz RohWerkst 60 (4), 291–296.

Thomson, A., Walker, P., 2013. Condition monitoring and durability assessment of straw bale construction. In: Portugal SB13: Contribution of Sustainable Building to Meet EU 20-20-20 Targets, pp. 791–798.

Thomson, A., Walker, P., 2014. Durability characteristics of straw bales in building envelopes. Constr. Build. Mater. 68, 135–141.

Thwe, K.L., 2003. Environmental effects on bamboo-glass polypropylene hybrid composites. J. Mater. Sci. 8, 363–376.

Thygesen, A., 2006. Properties of hemp fibre polymer composites—an optimisation of fibre properties using novel defibration methods and fibre characterisation (PhD Thesis). Risø-PhD; No. 11 (EN).

Tröger, F., Wegener, G., Seemann, C., 1998. Miscanthus and flax as raw material for reinforced particleboards. Ind. Crop. Prod. 8 (2), 113–121.

Tuzcu, T.M., 2007. Hygro-Thermal Properties of Sheep Wool Insulation (Master Thesis). TU Delft, Delft, The Netherlands.

UT, 2016. Turvas. University of Tartu, Geological Museum. http://www.ut.ee/BGGM/maavara/turvas.html (Accessed 23.03.2016).

Van Acker, J., Devos, J., De Geyter, S., Stevens, M., 2000. Bamboo as a raw material for wood processing in Europe. In: Paper presented at a IUFRO meeting, Kuala Lumpur, 9 August 2000.

Van Der Lugt, P., Van Den Dobbelstenn, A., Abrahams, R., 2003. Bamboo as a building material alternative for western Europe? A study on the environmental performance, costs and bottlenecks of the use of bamboo (products) in western Europe. J. Bamboo Rattan 2 (3), 205–223.

Vandenbossche, V., Rigal, L., Saiah, R., Perrin, B., 2012. New agro-materials with thermal insulation properties. In: Proceedings of the 18th International Sunflower Conference. Mar del Plata, Argentina, pp. 949–954.

Vardy, S, 2009. Structural behaviour of plastered straw bale assemblies under concentric and eccentric loading (PhD Thesis). Queen's Univ., Kingston, ON.

Vardy, S., MacDougall, C., 2006. Compressive testing and analysis of plastered straw bales. J. Green Build. 1 (1), 63–79.

Vardy, S., MacDougall, C., 2012. Concentric and eccentric compression experiments of plastered straw bale assemblies. J. Struct. Eng. 139 (3), 448–461.

Ventura, A., Idir, R., Marceau, S., Van Schoors, L., Andrianandraina, A., 2012. How to use LCA to assess materials as eco-design parameters in construction projects? In: Rilem, International Symposium on Life Cycle Assessment and Construction, IFSTTAR, Nantes, pp. 89–96.

Veri, V., Teppand, T., 2014. Pria pindalatoetustega haaratud aladel kasvavate taimede soojustehniliste omaduste uurimine (Thermal properties of growing plants in PRIA growing support areas). Katsete raport (Test report). EstUnivLifeSc, Tartu, 43 p.

Verma, C.S., Chariar, V.M., Purohit, R., 2012. Tensile strenght analysis of bamboo and layered laminate bamboo composites. Int. J. Eng. Res. Appl. 2, 1253–1264.

von Pettenkofer, M., 1858. Besprechung allgemeiner auf die Ventilation bezüglicher Fragen. Cotta, Munich, Germany.

Wall, K., Walker, P., Gross, C., White, C., Mander, T., 2012. Development and testing of a prototype straw bale house. Proc. Inst. Civ. Eng. Constr. Mater 165 (6), 377–384.

Wang, C., Xian, Y., Cheng, H., Li, W., Zhang, S., 2015. Tensile properties of bamboo fiber-reinforced polypropylene composites modified by impregnation with calcium carbonate nanoparticles. Bioresources 10 (4), 6783–6796.

Ward, R.J., Willis, H.A., George, G.A., Guise, G.B., Denning, R.J., Evans, D.J., Short, R.D., 1993. Surface analysis of wool by X-ray photoelectron spectroscopy and static secondary ion mass spectrometry. Text. Res. J. 63, 362–368. http://dx.doi.org/10.1177/004051759306300609.

WEC, 2016. Energy Resources. PEAT. World Energy Council. http://www.worldenergy.org/data/resources/resource/peat/. (Accessed 24.03.2016).

Wells, W.F., 1943. Air disinfection in day schools. Am. J. Public Health Nations Health 33, 1436–1443.

WHO, 2000. The right to healthy indoor air. Report on WHO Meeting No., WHO, Bilthoven.

Wöhler, A., Moschner, C.R., Gellerich, A., Militz, H., Greef, J.M., 2016. Provenances and properties of thatching reed (Phragmites australis). Appl. Agric. For. Res. 66, 1–10 (online first).

Xu, Q., Harries, K., Li, X., Liu, Q., Gottron, J., 2014. Mechanical properties of structural bamboo following immersion in water. Eng. Struct. 81, 230–239.

Yates, T., 2006. The use of non-food crops in the UK construction industry. J. Sci. Food Agric. 86 (12), 1790–1796.

Youngquist, J.A., English, B.E., Scharmer, R.C., Chow, P., Shook, S.R., 1994. Literature review on use of nonwood plant fibers for building materials and panels. General Technical Report FPL-GTR-80. USDA, Forest service, Forest Products Laboratory, pp. 1–148.

Yu, Y., Wang, H.K., Lu, F., Tian, G., Lin, J., 2014. Bamboo fibers for composite applications: a mechanical and morphological investigation. J. Mater. Sci. 49, 2559–2566.

Zach, J., Korjenic, A., Petránek, V., Hroudová, J., Bednar, T., 2012. Performance evaluation and research of alternative thermal insulations based on sheep wool. Energ. Buildings 49, 246–253. http://dx.doi.org/10.1016/j.enbuild.2012.02.014.

Zakikhani, P., Zahari, R., Sultan, M.T.H., Majid, D.L., 2014. Extraction and preparation of bamboo fibre-reinforced composites. Mater. Des. 63, 820–828.

Zhang, J., 2011. Experimental study of burning behaviors of intumescent coatings and nanoparticles applied on flaxboard. J. Fire Sci. 29 (6), 519–530.

Zhang, J., Zhang, H., Lai, K., Hao, X., Ma, T., Zhang, J., Ji, Y., Yan, Z., Zhou, Y., Sun, R., 2009. Structure and Properties of China Hemp Fiber. Chemical Industry Press, Uitikon Waldegg, Switzerland, 34–55.

Zhang, J., Delichatsios, M.A., McKee, M., Ukleja, S., 2012. Experimental and numerical study of burning behaviors of flaxboard with intumescent coating and nanoparticles in the cone calorimeter and single burning item tests. Fire Mater. 36, 554–564.

Protection of the bio-based material

4

4.1 Introduction

M. Humar
University of Ljubljana, Ljubljana, Slovenia

Wood is one of the most important building materials. When used in outdoor applications, wood is frequently exposed to weathering and is thus prone to fungal degradation and other degradations. However, it should be considered that degradation can be slowed down but cannot be fully prevented. Although degradation processes are not desired when wood is used in service, these processes are required and necessary in nature. If there would be no degradation of lignocellulosic materials, the CO_2 in nature would disappear in 30–50 years. Besides fungi, there are other organisms that can affect the performance of wood in outdoor applications. In warmer climates, termites predominantly affect the service life of wood and wood-based materials. It is expected that risks associated from termites will increase in the near future, mainly due to the climate change.

There are various solutions available for preventing degradation. Traditionally, users rely on a classical biocidal preservation and use of tropical durable wood species. Due to increased environmental awareness, the majority of the classical biocides have been removed from the market in the European Union (*EU*). There are only two remaining high-performance active ingredients available that can be utilised for impregnation of wood in ground contact and/or in sea water applications, copper and creosote. However, it is likely that creosote, the one of the oldest wood preservatives, will be removed from the market as soon as alternatives will be developed. Hence, only copper-containing formulations are likely to remain.

Use of tropical wood species is decreasing in Europe, predominately due to the environmental awareness. End users are now aware of deforestation issues in Africa, South America and Asia, hence, many try to avoid the use of tropical wood species, even if it has been sourced from certified forests.

Hence, there is a clearly visible need for alternatives. One of the alternatives developed is wood modification. Modified wood is often perceived to be an environmentally friendly alternative to classical wood preservation and the use of tropical wood species, respectively. There have been numerous modification techniques demonstrated at a laboratory-scale, but only a few have been successfully commercialised to date. One of the key reasons that slows down market penetration is the comparative higher price compared with alternatives already on the market. Cheaper alternative to wood modification are surface coatings. Surface coatings, if applied correctly, can result in improved service life and better aesthetic performance of wood.

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00004-5
© 2017 Elsevier Ltd. All rights reserved.

4.2 Potential hazards and degrading agents

C. Brischke[*,†], *W. Unger*[‡]
[*]Leibniz University Hannover, Hannover, Germany
[†]University of Göttingen, Göttingen, Germany
[‡]University of Applied Sciences Potsdam, Potsdam, Germany

The hazards associated with degradation are usually based on the influence of external biological factors onto bio-based building materials but can also be influenced by the conditions in service, such as temperature and moisture levels. Continual exposure to favourable conditions will allow an increased risk of biological risk by fungi, bacteria, insects, termites and marine borers. The following sections will consider some of the risks associated with examples of these degradative risks.

4.2.1 Moisture

Organic materials are generally hygroscopic and consequently subject to wetting when exposed outdoors or elsewhere submitted to high relative humidity. Moisture uptake through adsorption or capillary suction and condensation has a strong effect on several properties of lignocellulose and other bio-based building materials. Within the hygroscopic range, lignocellulose undergoes dimensional changes due to swelling and shrinking, a reduction of strength and hardness, and changes in acoustic, thermal and electrical properties. Since the majority of bio-based building materials are prone to biological degradation and all potential decay organisms require certain moisture levels, changes in moisture content also affect durability and thus the serviceability of building components. A more detailed description of moisture-related effects on the performance of wood and other bio-based building materials is given in Section 5.4.

4.2.2 Fungi and bacteria

4.2.2.1 Decay fungi

Fungi and bacteria can cause damage to organic building materials and hereby affect their optical appearance or functional performance. A generally accepted system for classifying the various potential damage-causing fungi does not exist, and classifications in use underwent periodic changes in the past. Table 4.1 provides an overview of the most relevant groups of fungi and provides important examples for each of them. Several compendia are available where more detailed information about the systematic, morphology, physiology, occurrence and particular characteristics are provided (e.g. Rayner and Boddy, 1988; Eaton and Hale, 1993; Unger *et al.*, 2001; Huckfeldt and Schmidt, 2006; Schmidt, 2006; Schwarze *et al.*, 2013). Within this section, only a brief description of the most relevant parameters related to fungal decay of wood and other lignocelluloses can be given.

Decay fungi can cause severe rot coming along with remarkable loss in mass and strength (Wilcox, 1978; Winandy and Morrell, 1993). There are three types of fungal

Table 4.1 Discolouring and destroying fungi that attack wood and other bio-based building materials

Destroying fungi			Staining fungi		Surface moulds
Brown-rot fungi	**White-rot fungi**	**Soft-rot fungi**	**Blue-stain fungi**	**Other stain fungi**	
Basidiomycetes	**Basidiomycetes (ascomycetes)**	**Ascomycetes, deuteromycetes**	**Ascomycetes, deuteromycetes**	**Ascomycetes, deuteromycetes**	**Ascomycetes, deuteromycetes**
For example, *Coniophora puteana*[a,b], *Serpula lacrymans*, *Postia placenta*[a,b], *Gloeophyllum trabeum*[b], *G. sepiarium*, *G. abietinum*, *Antrodia vaillantii*	For example, *Trametes versicolor*[a,b], *Donkioporia expansa*, *Schizophyllum commune*, *Phanerochaete chrysosporium*, *Pleurotus ostreatus*	For example, *Chaetomium globosum*[c], *Phialophora* spp., *Monodictys* spp., *Humicola grisea*[c], *Petriella setifera*[c], *Lecythophora mutabilis*[c], *Trichurus spiralis*[c]	For example, *Aureobasidium pullulans*, *Ceratocystis* spp., *Ophiostoma* spp., *Ceratocystiopsis* spp.	For example, *Discula* spp., *Arthrographis cuboidea*, *Chlorociboria aeruginosa*	For example, *Paecilomyces variotii*, *Aspergillus niger*, *Trichoderma* spp., *Bisporia* spp., *Penicillium* spp.

[a] Test fungus according to CEN/TS 15083-1 (CEN, 2015a).
[b] Test fungus according to EN 113 (CEN, 1996).
[c] Test fungus according to ENV 807 (ENV, 2001).
Modified from Unger *et al.* (2001) and Schmidt (2006).

rot that differ in decomposition of the material, exterior appearance of the substrate and to some extent in the physiological needs of the respective decay fungi. One distinguishes brown rot, white rot and soft rot. However, it is possible that more than one rot type occurs on the same piece of substrate either temporally parallel or in terms of a succession (Schmidt, 2006; Råberg *et al.*, 2007). Furthermore, several fungal species show signs of decomposition that refer to more than one rot type (e.g. Kleist and Schmitt, 2001).

Brown-rot-causing fungi degrade predominantly hemicelluloses and cellulose, but not lignin (Fig. 4.1). Consequently, wood and other lignocelluloses degraded by brown-rot fungi have a brown to black-brown colour due to the absence of cellulose and remaining brown lignin. Furthermore, the substrate shows superficial deformation and cubic fractures due to damage of cellulose. Most brown-rot fungi attack preferably softwoods, whilst hardwoods are more frequently attacked by white- and soft-rot fungi.

White-rot fungi degrade hemicelluloses, cellulose, and lignin, either simultaneously or successively. Lignocellulose attacked by white-rot fungi looks bleached and whitish and suffers from fibrous fractures (Fig. 4.1).

Brown-rot fungi belong to the basidiomycetes, whilst white rot is caused by basidiomycetes and ascomycetes. The third group of rot fungi is the soft-rot-causing fungi containing ascomycetes and deuteromycetes (*fungi imperfecti*). Soft rot is considered as a separate rot type, but the fungi are basically equipped with the same enzymes as brown-rot fungi. They are principally able to degrade both polysaccharides and lignin, but lignin is degraded at a later stage, and decay in general is considered to be at slower rates. A more detailed description of the different rot types and characteristics of single fungal species is, for instance, given by Eaton and Hale (1993), Unger *et al.* (2001), Huckfeldt and Schmidt (2006) and Schmidt (2006).

Growth and decay of fungi are affected by numerous factors such as nutrients, water, temperature, oxygen, pH value, light and gravity (Brischke *et al.*, 2006; Schmidt,

Fig. 4.1 Left, severe brown-rot decay on a Norway spruce (*Picea abies* Karst.) fence picket showing cubic fracture characteristics. Right, white-rot decay on terrace door corner joint made from tropical hardwood showing bright and fibrous wood substance.
From: L. Meyer-Veltrup.

2006). Their presence in a species-specific range is essential for growth, decay, or reproduction, and therefore, their absence prohibits fungal decay of bio-based building materials. The overall rule of protecting organic building material is consequently to ensure that at least one essential parameter is out of the required range, for instance, through keeping away moisture (i.e. no transport of fungal enzymes due to the lack of water) or impregnation with toxic preservatives (i.e. no nutrients due to poisonous substrate). Other factors such as temperature and oxygen content are difficult to adjust in a way that living conditions for fungi are compromised without affecting the living conditions for humans. However, high temperatures can be used for combat measures, and extremely low oxygen content is used to avoid attack by blue-stain and decay fungi when freshly felled wood is stored for longer periods by the use of foil tents (Rademacher *et al.*, 2010). Tables 4.2 and 4.3 give an overview of the physiological needs related to different wood-decay fungi (giving an indication for other lignocelluloses as well). It is commonly accepted that fungal decay requires moisture content above fibre saturation. However, more recently several studies showed that different fungi are able to degrade lignocellulose remarkably below fibre saturation at least if an external moisture source is provided and nearby. Furthermore, the minimum moisture content for growth of fungi on organic substrates is even smaller compared with the threshold for fungal degradation of lignocellulose (Huckfeldt and Schmidt, 2006; Meyer and Brischke, 2015).

The temperature requirements for fungal activity depend on the experimental set-up with respect to moisture conditions and supply of nutrients. One needs to distinguish between temperatures needed for growth and decay and lethal temperatures, which are much higher, typically between 55°C and 105°C depending on the respective experimental conditions (Huckfeldt and Schmidt, 2006).

Table 4.2 Physiological needs with respect to moisture for decay of wood by selected fungi

Fungus	Moisture content (%)			Source
	Min	Opt.	Max	
Coniophora puteana	21.5	36.4–210.0	>200	Huckfeldt and Schmidt (2006)
	22.3–29.7	29.0–76.1	na	Meyer and Brischke (2015)
	27.4	64.3	na	Stienen *et al.* (2014)
Serpula lacrymans	26.2	45.0–208.0	>200	Huckfeldt and Schmidt (2006)
Donkioporia expansa	27.0	34.4–126.0	>200	Huckfeldt and Schmidt (2006)
	18.9–52.3	57.6–120.0	na	Meyer and Brischke (2015)
	34.9	74.3	na	Stienen *et al.* (2014)
Gloeophyllum trabeum	30.7	45.7–179.0	>200	Huckfeldt and Schmidt (2006)
	16.3–37.1	47.3–172.8	na	Meyer and Brischke (2015)
Trametes versicolor	14.6–42.2	46.6–113.1	na	Meyer and Brischke (2015)

Test data differ with respect to wood species used. Test set-up was not identical, but in all studies, an external moisture was provided in the form of malt agar.

Table 4.3 Temperatures needed for optimal activity and growth of different decay fungi according to Huckfeldt and Schmidt (2006)

Fungus	Temperature (°C)	
	Optimum	Growth
Coniophora puteana	20–32	0–40
Serpula lacrymans	17–23	0.1–27
Donkioporia expansa	24–30	10–35
Gloeophyllum trabeum	30–38	5–45
Trametes versicolor	25–30	5–40

Compared with decay fungi and lignocellulose-destroying insects, bacteria cause less severe damage. However, different types of bacteria have the potential to degrade lignocellulose under partly extreme climatic conditions, for example, at very high moisture contents (e.g. Kretschmar *et al.*, 2008). Furthermore, bacteria can cause discolouration and increase the permeability due to destruction of pit membranes (Blanchette, 2000), and they have the potential for detoxification of natural or artificial wood-protecting ingredients (Greaves, 1971). Accelerated degradation has been observed when bacteria and decay fungi decompose wood simultaneously (Unger *et al.*, 2001). Bacteria that are able to destroy wood cell walls are further subdivided into erosion bacteria, tunnelling bacteria, and cavity-forming bacteria (Schmidt and Liese, 1994; Daniel and Nilsson, 1998; Kim and Singh, 2000).

4.2.2.2 Discolouring fungi

Besides structural changes of building materials, which can significantly affect their functional performance, fungi can affect the quality of building materials by discolouration. Discolouration can occur in living plants, harvested raw material, and in service due to different biotic and abiotic causes (Bauch, 1984; Koch *et al.*, 2002). Lignocellulose-discolouring moulds and staining fungi live on nutrients in the living parenchyma cells (Schmidt, 2006) and do cause no or only little damage to the cell wall structure.

Mould fungi belong to the group of *fungi imperfecti* and cause superficial discolouration but have also the potential to provoke allergic reaction of inhabitants. Mould can therefore be both an indoor and outdoor problem usually related to humidity, ventilation and condensation issues, frequently occurring in the building envelope. Mould growth is neither restricted to building nor to organic materials. Inert materials that are contaminated with, for instance, pollen are affected by mould and different foods.

Blue stain (sap stain) is a usually blue to black discolouration caused by different ascomycetes and deuteromycetes that can be superficial or penetrate deeply into the wood (e.g. Zink and Fengel, 1989). Besides discolouration, the hyphae of blue-stain fungi can penetrate through the pit torus into axial cell elements and consequently increase permeability of otherwise refractory lignocellulosic materials (Schmid and Liese, 1966; Schmidt, 2006). Substrates with heterogeneous permeability suffer from spotted appearance due to local differences in retention of stains and coatings.

4.2.3 Insects

4.2.3.1 General

Lignocellulose is used by insects for food, shelter and breeding. The most common lignocellulose-destroying insects belong to the orders *Coleoptera* (beetles) and *Isoptera* (termites). They are referred to as wood-eating (xylophagous) insects. That means that they cannot live without wood or other lignocellulosic materials. All insects have a similar structure. They have three paired feet (gr. *Hexapoda*) and segmented bodies supported by exoskeletons, the hard outer covering mostly made of chitin. The segments of the body are organised into three distinctive but interconnected units or tagmata: a head (the caput), a chest (the thorax) and the posterior (the abdomen).

The insects pass through a transformation (metamorphosis) during their life span. The beetles embrace four developmental stages (holometabolism), egg, larvae, pupa and adult (the complete insect—imago). From the wood-eating insects, the larval stage is the most important one and takes the longest time from the whole development; one generation is from the egg to the adult. Termites undergo an incomplete transformation (hemimetabolism). They omit the pupal stage, that is, larvae and adults show the same morphology.

4.2.3.2 Coleoptera (beetles)

The beetle morphology is characterised by front wings at the second and the third thorax segment. The outer wings are highly chitinised and cover the rest of the body. The first thorax segment often takes a neck shield, which covers the head. Beetles have biting jaws (mandibles) enabling them to chew, for instance, wood particles. The physiological development of the larvae of beetles is controlled by three factors, nutrients, moisture and temperature. An overview on the requirements of some wood-destroying beetle larvae is given in Table 4.4.

The common furniture beetle (*Anobium punctatum)* can utilise cellulose as a nutrient, because they have symbionts in their guts. The larvae can live in very old softwood and hardwood (Table 4.5). In contrast, the larvae of the powder-post beetle (*Lyctus brunneus*) can only live in the sapwood of hardwood deciduous trees, and they tend to grow faster with higher starch content present. The larvae of the house longhorn beetles (*Hylotrupes bajulus*) grow faster if the content of protein is sufficiently high. Consequently, these larvae can live in wood older than 60 years, but they will need to

Table 4.4 Nutrient requirements of the larvae of some wood-destroying beetles

Species	Chemical compounds
Anobium punctatum	Cellulose, proteins (small quantities)
Hylotrupes bajulus	Proteins, cellulose, polyoses, vitamin B
Lyctus brunneus	Starch, proteins, sugar, trace elements

Chemical compounds in order of importance.

Table 4.5 Wood-destroying beetles and corresponding food sources

Species	Softwood	Hardwood	Other characteristics
Anobium punctatum	X	X	–
Coelosthetus pertinax	X		Decayed wood
Ptilinus pectinicornis		X	Fine-porous heartwood
Priobium carpini	X		Decayed wood
Xestobium rufovillosum		X	Decayed oak wood (damped wood)
Hylotrupes bajulus	X		Sapwood
Lyctus brunneus		X	Sapwood

Table 4.6 Moisture and temperature requirements of relevant dry-wood insects

	Moisture content (%)			Temperature (°C)			
Species	Min	Optimum	Max	Min	Optimum	Max	Lethal
Anobium punctatum	10–12	28–30	50–57	12	21–24	29	50–57
Hylotrupes bajulus	9–10	30–40	65–80	16–19	28–30	35	55–57
Lyctus brunneus	7–8	14–16	23	18	26–27	30	49–65

eat more to have enough protein to allow required levels of growth, and thus, they tend to need more time to grow up until the pupae stage.

Wood-destroying beetles can be characterised according to their nutrient preferences as shown in Table 4.5. For instance, the larvae of the house borer (*Coelostethus pertinax*) and the death watch beetle (*Xestobium rufovillosum*) grow faster in decayed wood (Table 4.5).

The most relevant beetle species are those living in buildings and belonging to the dry-wood insects. The physiological needs of those insects are shown exemplarily for selected species in Table 4.6. In contrast to lignocellulose-degrading fungi, these insects require less moisture but higher temperatures for growth and degradation of lignocellulose.

The life cycle of wood-destroying beetles is quite different from that of wood-decaying fungi. Table 4.7 shows stimulating and inhibiting effects on the different phases of development exemplarily for *A. punctatum*. Beetles fly towards wooden objects to find new nutrient sources. Knowledge about their different life cycle phases is essential to select appropriate protection measures for lignocellulosic materials and built structures. Furthermore, the surface structure of the lignocellulose substrate is an important parameter for insect attacks. Rough surfaces with cracks tend to attract female beetles to lay their eggs more so than smooth surfaces.

Table 4.7 Stimulating and inhibiting effects on the different phases of development of *Anobium punctatum*

Phase of development	Effect	
	Stimulation	**Inhibition**
Copulation of adult beetles	Darkness (photophobia)	Light
Egg-laying	Oak sapwood, lime, poplar, willow, hazelnut Old emergence passages, cracks, fissures, darkness	Smooth, closed surfaces
Larvae development (ovum larvae to pupation)	21–24°C air temperature Until 95% *RH* 28%–30% *MC*	more than 29°C air temperature <55% RH <10% MC
Pupation	Extended cool period (5 months with average temperature at 5°C)	Cool period too short and too warm
Emergence and flight	Warm but not too warm noon hours	Too high or too low temperatures at noon

4.2.3.3 Anobiidae *(furniture beetles)*

The adult beetles of the *Anobiidae* family are only a few millimetres in size and brown in colour. A typical characteristic is a neck shield that covers the head like a hood. The circular exit holes have a diameter between 1 and 4 mm. The anobiid larvae measure only a few millimetres in length and are white to yellowish. They can be identified by their significant differences in habit (Unger and Unger, 1986).

A. punctatum (common furniture beetle)

Adults are dark brown with rounded to cylindrical bodies. The neck shield is knobbed and extends over the head. The antennae are finely jointed into 11 segments. The wing surfaces bear closely spaced rows of dots. The name *punctatum* indicates a helpful feature for destining this important beetle.

Beetles are very good flyers; they swarm from Apr. to Aug.; the temperature needs to be above 18°C. During swarming, the male beetles can be indicated by insect traps that contain the female sex hormone stegobinone (Fig. 4.2).

The adults do not feed and live only for 1–3 weeks. Twenty to forty eggs are deposited by the female into fine cracks in wood or into old galleries. The larvae time in the

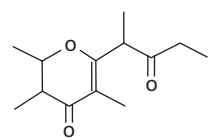


Fig. 4.2 Chemical structure of stegobinone (sex hormone of female *A. punctatum*).

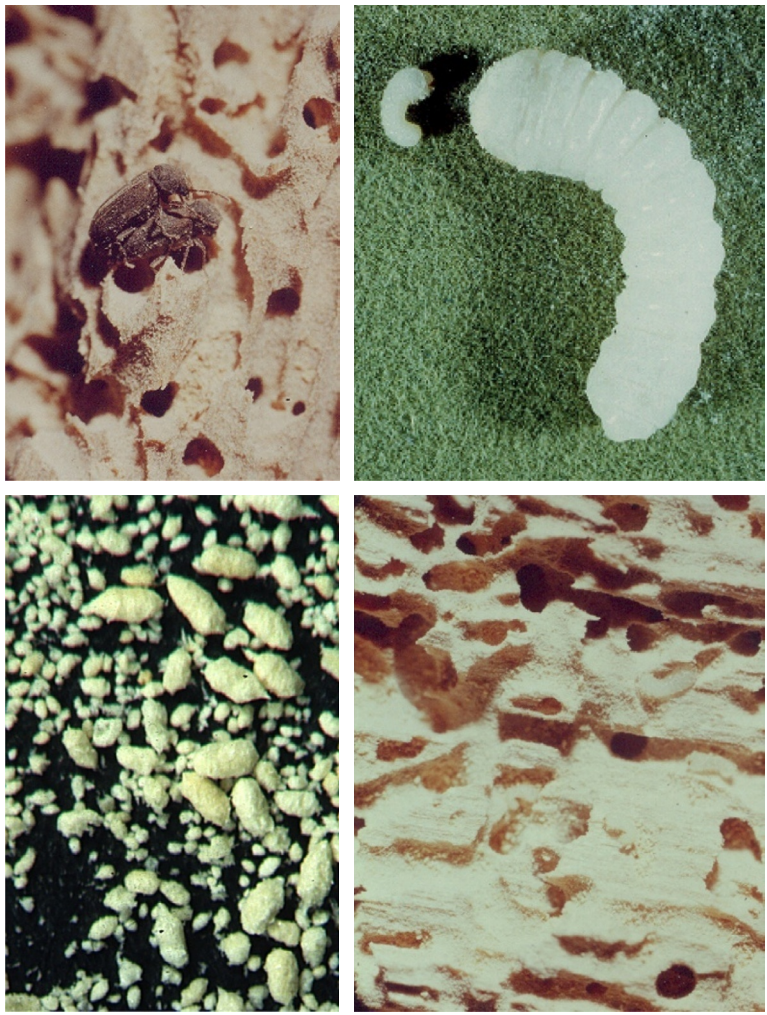


Fig. 4.3 *Anobium punctatum*. Top left, pair of adult beetles. Top right, larvae of *A. punctatum* (left) and *H. bajulus*. Bottom left, faecal pallets. Bottom right, galleries.

wood depends on different physiological parameters and is between 2 and 8 years. The galleries of the larvae (Fig. 4.3) are irregular and 1–2 mm in diameter and filled with typical pellets (Fig. 4.3). Feeding proceeds mostly to the wood surface but never at the surface. The exit holes are also circular and 1–2 mm in diameter.

Frequently, *A. punctatum* attacks not only furniture, sculptures, picture frames, panel paintings, altars, flooring and stairs but also structural timber. *A. punctatum* is widely distributed in Europe, especially in England and Ireland, but has been introduced also to North America, South Africa, South Australia and New Zealand.

4.2.3.4 Cerambycidae *(longhorn beetles)*

The *Cerambycidae* differ from other wood-destroying beetles by their body size of 10–30 mm and their long and curved antennae (eponymous for the family). Also, the larvae of the *Cerambycidae* are rather long (10–25 mm). Most species are greenwood insects, though dry wood in use is attacked mainly by the house longhorn beetle (*H. bajulus*).

H. bajulus (house longhorn beetle)

Adults are dark to black-brown with whitish-grey hairs. They do not feed and live only about 14 days. Wing surfaces are shiny with light, V-shaped cross-ties that are made up of very small hairs. Antennae are 11-jointed and curved. The neck shield has two shiny black spots. Females have an ovipositor and are longer than the males (Fig. 4.4).

Swarming takes place from Jun. to Aug. during the hot midday hours. Females use the egg duct to lay 200–400 eggs, with the larvae emerging after 10–20 days and proceed to immediately bore into the wood. The development of the larvae takes place over six periods of moulting. The duration of the larvae stage can be between 3 and 10 years, depending on the environment. Pupation takes place in pupal chambers close to the wood surface after longer cold periods.

Exit holes are irregular and oval (Fig. 4.4), whilst the galleries in the wood are oval. Larvae feed primarily in the sapwood of softwoods (Fig. 4.4), excreting cylindrical faecal pellets. During the summer months, rasping feeding noises of the larvae can be detected.

Newer structural timbers with a very low proportion of heartwood are more at risk than older ones with higher proportions of heartwood. *H. bajulus* is distributed in Europe, Asia Minor, Africa, America and New Zealand.

Fig. 4.4 *Hylotrupes bajulus*. Top left, pair of adult beetles. Top right, cross section of softwood rafter with severe attack. Bottom left, larvae. Bottom right, bore holes.

4.2.3.5 Lyctidae (powder-post beetles)

The lyctid beetles, which are brown and just a few millimetres long, form a family composed of about 60 species with worldwide distribution. Only the larvae will live inside the wood and destroy only the sapwood of hardwood species, leaving the heartwood intact. As a dry-wood pest with very low moisture requirements—minimum about 7%–8%—and a very short generation period of 3–12 months, they cause great damage. Infected wood is often apparently intact, and damage can stay undetected.

L. brunneus (brown powder-post beetle)

Adults are active at night and very good flyers. They are reddish brown to black brown with slender bodies 2.5–8 mm long. The neck shield is trapezoidal and the wing surfaces with rows of dots. The 11-jointed antennae end in two-jointed clubs.

Swarming takes place at the optimum temperature of 26–27°C. Females will lay about 75 eggs into open vessels. Under optimum conditions, the larval development period is very short at 4 months.

Exit holes are circular and 1.0–1.5 mm in diameter. The galleries are 1–2 mm wide and are similar to those of *A. punctatum*. The frass of the lyctid larvae is extremely fine and light coloured powder, which does not form typical faecal pellets (the difference to *A. punctatum*). The sapwood is completely pulverised leaving only a thin surface layer, hence the name powder-post beetle.

4.2.3.6 Isoptera (termites)

Termites (*Isoptera*) form an order of insects that are closely related to that of the cockroaches (*Blattidae*). *Isoptera* and *Blattidae* have the same protozoan intestinal symbionts (polymastiginas). They undergo an incomplete transformation (hemimetabolism). Termites are often referred to as 'white ants' because of their colour. Their surface is weakly chitinised, and they avoid light. They are not ants, but there are certain parallels in their habit. Termites are also social insects forming colonies and often exhibit marked polymorphism with different caste formations.

Termites live mainly in tropical and subtropical regions. They require warmth and moisture. Termites prefer a temperature of 26–32°C and a relative humidity of 70%–90%. Their natural distribution is confined to regions south of the 10°C yearly isotherm (Fig. 4.5).

More than 2000 species of termites are known. About 30 species are of economic significance with regard to damage to wood structures. The number of individuals in a termite colony can range from 1000 to 2 million. The body length of these small-sized insects is 10 mm.

A colony consists of three great castes and developmental stages, namely, fertile reproductive and infertile soldiers and workers (Fig. 4.6). In addition to these castes, there are numerous developmental stages such as eggs, larvae without wings, nymphs with wing pads and presoldiers. They are controlled primarily by the reproductive in an oral feeding system by way of nutrient exchange (trophallaxis) and hormonal influences.

Termites destroy softwoods, hardwoods, bamboo and other lignocelluloses, as well as numerous other organic materials. Termites are very dangerous pests of wood, but termites can also attack plastics and other building materials. Attacks by termites are often detected too late, because they leave the outer surface of the substrate intact whilst destroying the interior completely.

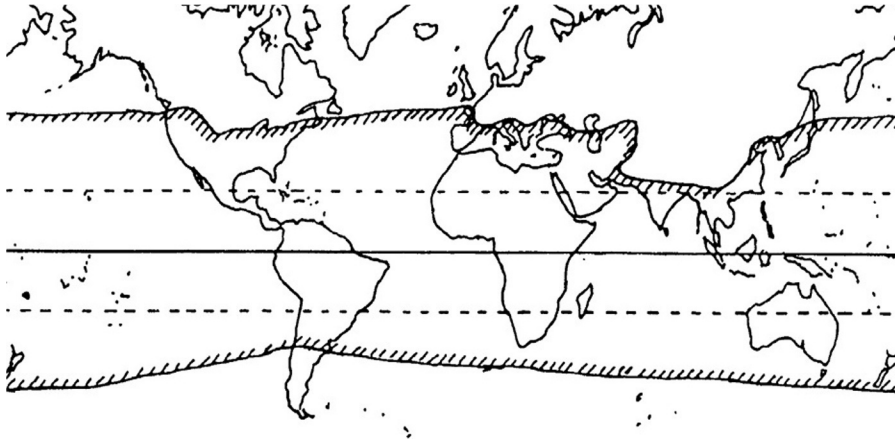


Fig. 4.5 Map of termite distribution.
From: Richardson (1993) cited in Unger *et al.* (2001).

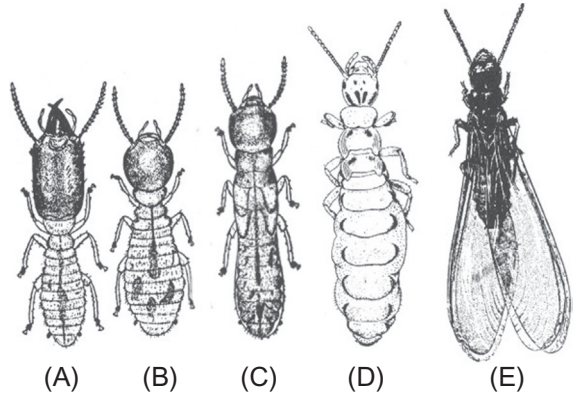


Fig. 4.6 Castes and development stages of termites of the genus *Reticulitermes*: (A) soldier, (B) worker, (C) nymph, (D) secondary reproductive and (E) primary reproductive.
From Unger *et al.* (2001).

Systematically, termites are divided into six families: Mastotermitidae, Termopsidae, Hodotermitidae, Termitidae, Kalotermitidae and Rhinotermitidae. On their habits, termites are classified into tree-dwelling, dampwood, dry-wood and subterranean termites. In the maintenance of buildings and newer organic construction materials, the subterranean termites and the Rhinotermitidae are of principal significance.

4.2.3.7 Subterranean termites

Most of the wood-destroying termites are subterranean termites. Important genera are *Mastotermes*, *Nasutitermes*, *Heterotermes*, *Reticulitermes* and *Coptotermes*. They establish nests in the earth or in dead wood. Workers traverse as much as 100 m between the nest and the attacked wood in buildings for instance. As a connection between the

earth and wood, they can form galleries. Termites move very quickly inside the galleries. The infested wood is also covered with these channels.

Rhinotermitidae

The Rhinotermitidae species have intestines in the stomach. In the past, the species *R. lucifugus* was found in Europe along the 46th latitude from the Atlantic coast to the Ukraine, mainly in the Mediterranean region. The species *R. flavipes* is native in the United States and has been introduced in Europe repeatedly. In Hamburg, Germany, infestations have existed for years. Reproduction appears to take place only through the secondary reproductive stage.

The species *R. santonensis* was formerly considered a variety of *R. lucifugus* but today is recognised as a separate species. It is found in the area around Paris and Bordeaux. In Europe, *R. santonensis* is used as a test termite to determine the biological efficacy of wood preservatives.

4.2.4 Marine borers

4.2.4.1 Teredinidae

The most important wood-destroying marine borers are found amongst the Bivalvia and Crustacea. The Teredinidae (shipworms) belonging to the Bivalvia include dangerous pests of objects such as ships, groyne, or jetties in salty sea water. The Teredinidae are elongated, whitish animals that depart significantly from the typical bivalve shape. Their distribution depends on the salt content of the water and its temperature. Warm climates favour their life processes, whilst cold temperatures slow down their activity. The most important species belong to the genera *Teredo* and *Bankia*. Adults of the genus *Bankia* are significantly larger, at a length of 1500–1800 mm, than those of the genus *Teredo* that grow to a length of 300–600 mm, although shipworms 2 m long have been recorded.

Shipworm is the common name of *T. navalis* L. that is distributed in coastal waters of warm and temperate zones. The shipworms are bisexual and produce annually 1–5 million eggs in three to four batches. After fertilisation in the womb, larvae develop within 14 days and are then expelled into the ocean water. The larvae, 0.3 mm long, attach themselves to wood after 1–3 weeks and begin to scrape. When the shell-like valves have developed into a boring utensil, shipworms can penetrate into the wood. About 23 days after attachment, their final shapes are formed, and rapid growth in the length takes place. In contrast to other bivalves, the shipworm uses the bore chips as a food source. The life of a shipworm lasts between 1 and 3 years. They attack softwoods and hardwoods and require a salt content in the water of 0.9%–3.5%. Shipworm can therefore be found in almost all European coastal areas, more recently also in the Baltic Sea due to increasing salinity (Leppäkoski *et al.*, 2002; Borges, 2014; Borges *et al.*, 2014 a,b; Appelqvist *et al.*, 2015).

Other species belong to the genus *Bankia*. The shipworm has a worm-like, extended, whitish body and deposits calcareous material on the surface of the borehole. At the head portion, shell-like valves are arranged in a circle. The serrated edges of the valves serve as boring instruments and allow the shipworm rapidly boring into the wood. At the rear end, two snoutlike hoses (siphons) protrude into the sea water. Adults are about 200–450 mm long.

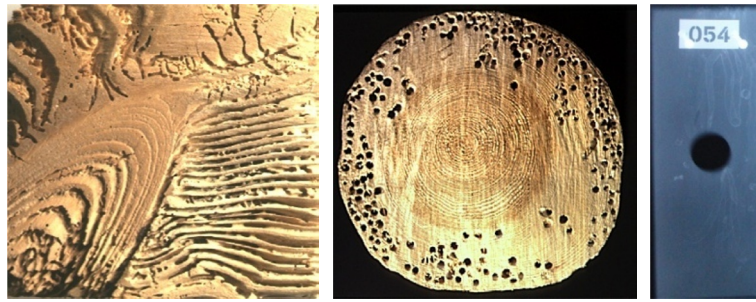


Fig. 4.7 Left, softwood attacked by *Limnoria lignorum*. Centre, cross section of softwood post attacked by *T. navalis*. Right, X-ray scan of wood specimen attacked by shipworms.

The wood is gnawed on the surface and studded with circular boreholes of 6–8 mm in diameter. The cross sections of severely damaged wood look like a sieve (Fig. 4.7). Shipworm attacks both sapwood and heartwood. The excavated burrow is usually lined with a calcareous tube that allows detecting shipworm by X-ray techniques even if no attack is visible from the outside (Fig. 4.7; Palma, 2005; Slevin *et al.*, 2015).

4.2.4.2 Limnoriidae

The Limnoriidae (gribble) belonging to the Crustacea live in shallow coastal waters of cold and temperate zones and can attack submerged wooden structures. They do not penetrate into the wood as deep as the Teredinidae and destroy it much more slowly. Their tunnels extend parallel to the wood surface, and as the outer layers are lifted off by wave action, the gribble gradually burrows more deeply into the wood. The genus *Limnoria* contains numerous species. One of the most common is *L. lignorum*, often just named gribble.

Gribbles are flattened, isopod-like creatures that are yellow-brown in colour and can roll themselves up. In Central Europe, they are 4–5 mm long and have strong mandibles with sharp edges. Wood serves as both food source and breeding shelter. The animals usually live in pairs for about 1 year in a borehole of 1.5–2 mm diameter. They require water with a salt content of 1.5%. *L. lignorum* is a cold-water species that does not develop well above 20°C. Breeding begins when temperatures reach 9–10°C.

The wood is damaged by round, winding bore tunnels that usually follow the early wood layers of softwood (Fig. 4.7). The tunnels do not penetrate more than 20 mm into the wood and have holes that serve for water exchange. The wood is destroyed layer by layer from the outside, and the destroyed and flaking layer can reach a depth of 6–12 mm in 1 year. Gribbles do occur in both softwoods and hardwoods of marine structures and in boats and shipwrecks.

4.2.5 Systems describing physical and biological hazards

The service class system according to Eurocode 5 (EN 1995-1-1, CEN, 2010-12) is mainly aimed at assigning strength values and for calculating deformations of structural timber members under defined environmental conditions (Table 4.8).

Table 4.8 Service classes according to EN 1995-1-1 (CEN 2010-12)

Service class	Description
1	Characterised by a moisture content in the materials corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 65% for a few weeks per year
2	Characterised by a moisture content in the materials corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 85% for a few weeks per year
3	Characterised by climatic conditions leading to higher moisture contents than in service class 2

Notes, in service class 1, the average moisture content in softwoods will not exceed 12% and in service class 2, the average moisture content will not exceed 20%.

In contrast, the use class (*UC*) concept according to EN 335 (CEN, 2013) defines exposure conditions for wooden commodities or building components with respect to both moisture-related use conditions and the potential occurrence of different groups of decay organisms such as wood-discolouring and decay fungi, beetles, termites and marine borers (Table 4.9). The UCs have some overlaps with service classes but are not directly transferable to each other. However, the UC system can be used to estimate the potential hazard for decay or other biotic attacks under certain use conditions but is still a rough instrument and does not allow precise performance prediction (Kutnik *et al.*, 2014).

Table 4.9 Use classes according to EN 335 (CEN, 2013)

Use class	General service conditions[a]	Occuring organisms[b,c]				
		Wood-disfiguring fungi	Wood-destroying fungi	Beetles	Termites	Marine organisms
1	Interior, dry	–	–	U	L	–
2	Interior or under roof, not exposed to weather, possibility of condensation	U	U	U	L	–
3	Exterior, without soil contact, exposed to weather. If class-divided 3.1. limited moist conditions 3.2. persistently moist conditions	U	U	U	L	–

Table 4.9 Continued

Use class	General service conditions[a]	Occuring organisms[b,c]				
		Wood-disfiguring fungi	Wood-destroying fungi	Beetles	Termites	Marine organisms
4	Exterior, in contact with soil or freshwater	U	U	U	L	–
5	Permanently or regularly immersed in salt water	U[d]	U[d]	U[d]	L[d]	U

[a] There are borderline and extreme cases for the use of wood and wood products. These can cause the result that a UC will be allocated, which differs from the definition of this standard.
[b] Protection against all listed organisms is not absolutely required because they do not occur under all use conditions and at all geographical locations or they are not economically significant or not able to infest specific wood products due to the specific state of the product.
[c] See Annex C.
[d] The area above water surface of certain wooden components can be susceptible to all stated organisms.
U = is spread all over Europe and in the area of the European Union
L = occurs locally all over Europe and in the area of the European Union

More advanced approaches of quantifying the risk for decay or mould growth have been developed and are described more in detail in Chapter 8. In first instance, different climate parameters such as precipitation, temperature, wind-driven rain (*WDR*) and relative humidity are used to quantify the effect of the outdoor environment on the performance of bio-based building materials reaching from simple climate indices to sophisticated exposure, decay, termite and mould models.

4.3 Material protection

M. Humar, E. Melcher†*
*University of Ljubljana, Ljubljana, Slovenia
†Thünen Institute of Wood Research, Hamburg, Germany

4.3.1 Introduction

The majority of the European wood species are classified according to EN 350-2 (CEN (1994)) with an insufficient durability for outdoor applications. In order to use these wood species in the more demanding applications, they have to be somehow protected. For this purpose, different kinds of inorganic or organic chemicals were used. The first reports of historical use of biocides purposed for wood protection were the use of tar oil for the protection of Noah's ark. In later centuries, there were some more or less effective alternatives developed, such as mercury chloride, olive oil or garlic dissolved in vinegar.

Industrial wood preservation, as recognised today, started in the middle/at the end of the nineteenth century, when technical processes were scaled up to the industrial level by Bethell, Boucherie, Burnett and Kyan (Liese and Gröger, 1954). However, the era of commercial pressure treatment began later on, with the impregnation of railway sleepers using creosote. It should be considered that oak was used for military purposes only at that period. Hence, the development of durable creosote crossties somehow enabled the development of both the railroad and telecommunication systems. Afterwards, treated wood was primarily used for more than a century for industrial, agricultural and utility applications. In the 1970s and 1980s, the use of preservative-treated wood begun to increase in other non-infrastructural applications. Connell (2004) reported that <5% of the total volume relates to poles, sleepers and marine end uses. Nowadays, more treated wood is used for construction and leisure applications than for infrastructure. In parallel to this trend, a need for less toxic and more environmentally friendly wood preservatives evolved.

4.3.2 Biocides

Wood preservation in the EU is well regulated. In the first period, wood protection was mainly dominated by chromated copper arsenate (*CCA*), pentachlorophenol (*PCP*) and creosote. For example, CCA has been widely used in Europe since the early 1950s. However, the use of widespread wood preservatives (CCA, creosote and PCP) has been restricted or even banned in the 1990s (Willeitner, 2001) in most of the EU member states. Major breakthrough was acceptance of the Biocidal Products Directive (*BPD* 98/08/EC). With the implementation of this directive, only 39 of 81 of the previous active ingredients remained on the market of wood preservation. Later on, the Biocidal Products Directive (BPD 98/08/EC) was replaced by the Biocidal Product Regulation (*BPR*) (Regulation (EU) 528/2012). As the registration of new active incidents (biocides) is rather expensive, in the past decade, there was no considerable development performed in the field of biocidal wood protection. The cost of the registration process for a new active ingredient in the EU is around €6 million. The introduction of micronised copper on the European market has been the only significant change that can be expected in the near future. A list of the approved active ingredients for wood protection can be seen in Table 4.10.

From Table 4.10, it can be clearly seen that almost half of the approved active ingredients were not used in any of the products on the Slovenian market. Additionally it can be seen that the number of biocidal products on the market considerably increased in the last few years. The number of listed wood preservatives in the database increased from 92 in 2010 to 110 in 2014. In the following year, a considerable gap was noticed. The prime reason for this occurrence originated in the existing legislation. All biocidal products have to be registered by the European Chemical Agency (*ECHA)*. The cost for the dossier is between €100,000 and €200,000 per biocidal product. Therefore, a lot of small producers decided to use formulated products (frame formulation) provided by the suppliers of the active ingredients to avoid the expenses related with registration and development of the product. Thus, small producers are preparing biocidal products based on the recipe provided by suppliers of active ingredients. This

Table 4.10 List of approved active ingredients in respective years compared with registered biocidal products in Slovenia

Approved active ingredient	*CAS*	Number of biocidal products with respective ingredient		
		2010	2012	2016
Total no. of products		92	100	350
Iodopropynyl butyl carbamate (*IPBC*)	55406-53-6	39	46	316
Propiconazole	60207-90-1	25	30	302
Tebuconazole	107534-96-3	5	9	46
Permethrin	52645-53-1	26	25	37
Alkyldimethylbenzylammonium chloride (*ADBAC*)	68424-85-1	8	13	17
Boric acid	10043-35-3	23	27	14
Copper(II) carbonate dihydroxide	12069-69-1	9	12	10
N-(3-Aminopropyl)-*N*-dodecylpropane-1,3-diamine	2372-82-9	1	1	3
Bardap 26	94667-33-1	1	1	3
Didecylpolyoxyethylammonium borate	214710-34-6	1	1	3
4,5-Dichloro-2-octyl-4-isothiazolin-3-one (*DCOIT*)	64359-81-5	9	9	2
Cypermethrin	52315-07-8	3	6	2
Dimethyldidecylammonium chloride (*DDAC*)	Mixture of chemicals	0	0	6
Alkyltrimethylammonium chloride (*TMAC*)	Mixture of chemicals	0	0	6
Disodium octaborate tetrahydrate—*DOT*	12280-03-4	4	4	2
Fenoxycarb	72490-01-8	1	3	1
Creosote	8001-58-9	2	2	2
Bis-(*N*-cyclohexyldiazeniumdioxy)-copper (Cu-HDO)	312600-89-8	0	2	1
Dichlofluanid	1085-98-9	5	4	1
Fenpropimorph	67564-91-4	1	1	1
Etofenprox	80844-07-1	1	1	0
Cu(II) oxide	1317-38-0	2	2	0
Tolylfluanid	731-27-1	1	0	0
Cyclohexylhydroxydiazene 1-oxide, potassium salt (K-HDO)	66603-10-9	0	0	0
Hydrogen cyanide	74-90-8	0	0	0
Thiabendazole	148-79-8	0	0	0
Thiadiazine	533-74-4	0	0	0
Sodium borate decahydrate	1330-43-4	0	0	0
Sulfuryl fluoride	2699-79-8	0	0	0
Boron oxide	1303-86-2	0	0	0
Copper(II) hydroxide	20427-59-2	0	0	0

Continued

Table 4.10 Continued

Approved active ingredient	*CAS*	Number of biocidal products with respective ingredient		
		2010	2012	2016
Potassium sorbate	24634-61-5	0	0	0
Benzalkonium chloride (*BKC*)	Mixture of chemicals	0	0	0
Flufenoxuron	101463-69-8	0	0	0
Thiamethoxam	153719-23-4	0	0	0
Clothianidin	210880-92-5	0	0	0
Bifenthrin	82657-04-3	0	0	0
Cyproconazole	94361-06-5	0	0	0
Chlorfenapyr	122453-73-0	0	0	0
Thiacloprid	111988-49-9	0	0	0

is clearly reflected from the list of the biocidal products on the Slovenian market, with 245 biocidal products out of 350 having the same composition, consisting of iodopropynyl butylcarbamate (IPBC) and propiconazole. These products are produced by various companies, in different colour varieties. Another change that can be noticed from the list of the biocidal products is a shift from a simple product consisting of only one active ingredient like boric acid and IPBC to more complex products consisting of two to four active ingredients that provide efficacy against variety of the pests, namely, staining fungi, decay fungi and insects. The reason for this change originates in the consumers perception of wood protection. If they choose a product protected with a wood preservative, they expect long-term efficacy.

However, these products are not intended to be used in heavy-duty applications. They are designed to be used in UC 2 (interior use, or under cover, not exposed to the weather: possibility of water condensation) and 3 (exterior use, above ground, exposed to the weather) applications like joinery, windows and facade. For heavy-duty applications, there are only two types of products available, copper-amine-based preservatives and creosote. However, creosote has been under a lot of pressure, with its use limited to railway cross-ties and utility poles. Creosote is only on the approved list until 2017, and afterwards, its status will be reconsidered. It is anticipated that creosote will be allowed until environmentally friendly alternatives are developed. There are many developmental projects ongoing across Europe to develop such effective and environmentally more acceptable alternative.

Table 4.10 provides only the composition of the biocidal products on the Slovenian market. Unfortunately, these data do not provide information about the market share of the respective products. However, it is possible to obtain such information for other European countries *via* online published wood preservative directories, for example, Austria (www.holzforschung.at/fileadmin/Content-Pool/PDFs/2016/Publikationen/Holzschutzmittelverzeichnis_2016_v3.pdf) or Germany (www.baua.de/de/Chemikaliengesetz-Biozidverfahren/Biozide/Produkt/Zugelassene-Biozidprodukte.html).

A comparison of the composition of approved wood preservatives for the do-it-yourself (*DIY*) sector illustrates that the majority of DIY products contain mainly organic active ingredients like IPBC, tebuconazole, propiconazole or pyrethroids. On the other hand, in the case of heavy-duty applications (UC 3.2 (exterior use, above ground, exposed to the weather: prolonged wetting conditions) and 4 (exterior use in ground contact and/or fresh water), EN 335 (CEN, 2013)), mainly copper-based preservatives were used for the pressure treatment of utility poles, highway fences, and infrastructural wood. Furthermore, considerable amounts of preservative solutions are used for the short-term protection of wood during transport in order to avoid discolouration.

4.3.3 Preservation techniques

The performance of preservative-treated wood depends on the biocides and the techniques applied to introduce the treatments into the wood. In doing so, it is necessary to consider which technique should be used based on the preservative chosen, the application and desired service life. Wood used in higher user classes requires more effective biocides and more advanced techniques.

For example, the majority of joinery is protected by superficial treatment processes, for example, brushing or short-term dipping. Dipping is the predominant method used for protection of wood in transport. A typical dipping plant is shown in Fig. 4.8. Dipping is a particularly good solution for wood that is used in less exposed application and for small companies that are not required to treat larger dimension wood. The quality of the treated product is predominately affected by the solution strength and immersion time. However, special attention should be given to constant monitoring of the concentration; as particularly during long-term dipping, selective adsorption of active ingredients may occur.

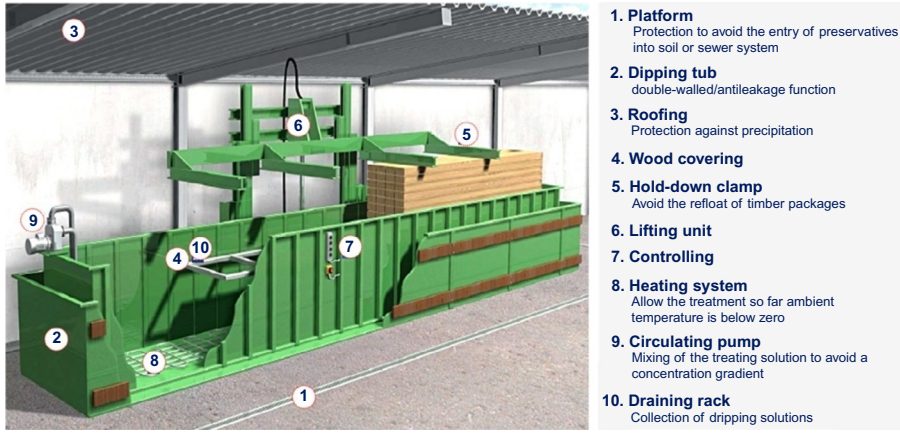


Fig. 4.8 Display of a dipping plant.
Based on or Courtesy Deutsche Bauchemie e.V., Frankfurt/Main.

Sometimes dipping is combined with the application of vacuum. Special chambers were developed where the wood batch was located in the vacuum chamber and the preservative solution sprayed on the specimens. The advantage of this method is that there is less preservative solution needed in the tank, it is faster than dipping, and, in general, there is better penetration achieved.

However, to meet higher penetration classes (EN 351-1, CEN, 2007), treating vessels have to be used, as presented on Fig. 4.9. This pressure plant enables vacuum and pressure regimes, with different pressures depending on the treatment method being used. In general, these plants use the Bethell regime—full cell process for water-based systems and the Rüping regime for creosote, though the latter requires a specially designed impregnation plant. The pressure applied during the process is typically between 10 and 12 bars, with the total duration of the impregnation between 6 and 16 h, depending on the impregnation requirements (e.g. DIN 68811, 2007).

Besides preservative solution and process applied, uptake and penetration also depend on the wood species (e.g. Nicholas and Siau, 1973 or Melcher and Zwiefelhofer, 2013). As can be seen from Fig. 4.10, Scots pine (*Pinus sylvestris*) sapwood is easily to impregnate, whilst larch (*Larix* spp.) and spruce (*Picea* spp.) wood are much more challenging. Typically, spruce is characterised by its extreme variability in impregnability (as shown in Fig. 4.11). Therefore, some of the electricity-transmitting companies avoid spruce for utility pole production.

Although beech (*Fagus* spp.) is easy to treat, its impregnability can be considerably affected especially in the case of red heart formation (Fig. 4.12). Therefore, sleepers with such abnormalities were excluded. Besides discolourations, penetration and retention can also be affected by moisture content of the wood. If the moisture content of the wood is above the fibre saturation point, preservative solution cannot penetrate into the cell lumina.

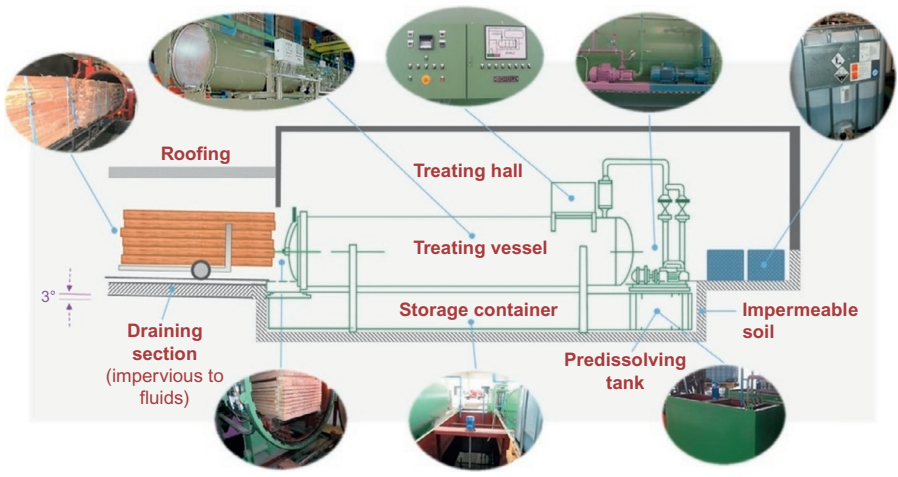


Fig. 4.9 Schematic display of a pressure plant.
Based on or Courtesy Deutsche Bauchemie e.V., Frankfurt/Main.

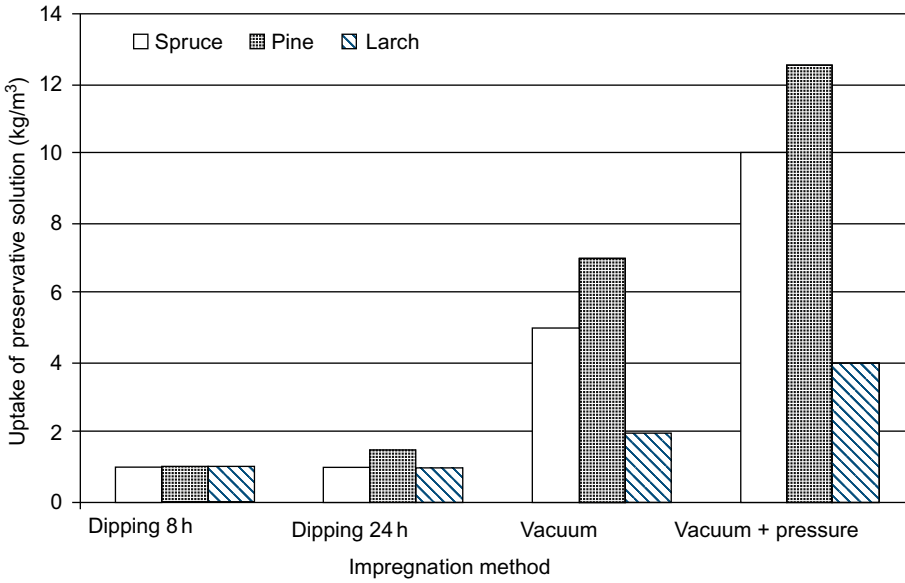


Fig. 4.10 Influence of impregnation procedure on uptake of copper-ethanolamine-based solution. The size of the specimens was $2.5 \times 5.0 \times 50$ cm^3 (Humar *et al.*, 2016b).

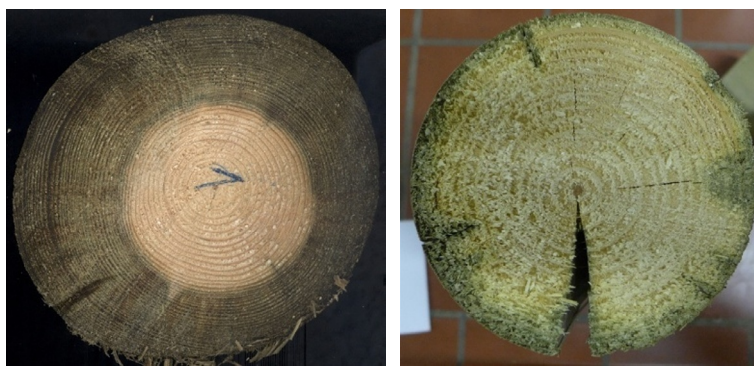


Fig. 4.11 Example of well-treated Scots pine and poorly treated Norway spruce with copper amine solutions.

4.3.4 *Influence of the preservation techniques on the performance*

One of the most challenging tasks is to achieve the retention and penetration requirements for certain UC. This is a must to meet performance requirements. In general, retention and the penetration class increase with increasing UC. However, there is always a conflict between expected performance and the cost of the product. A retention lower than described in the technical data sheet can lead to premature failure of the treated wood (e.g. Melcher and Müller, 2016; Humar and Thaler, 2017). On the other hand, surplus uptake does not make sense, due to both environmental and economic concerns.

Fig. 4.12 The presence of discolourations or red heart decreases the impregnability of beech wood with creosote as can be seen from the cross section of railroad tie.

Data presented in Fig. 4.13 clearly show that preservative retention has a considerable effect on the performance of preservative-treated wood. If insufficient retention of the biocidal solution is applied, wood degradation is not stopped, but only slowed down. This can be seen from the data of the copper-treated spruce exposed in the ground, according to EN 252 (CEN (2015b)). Spruce wood was almost completely

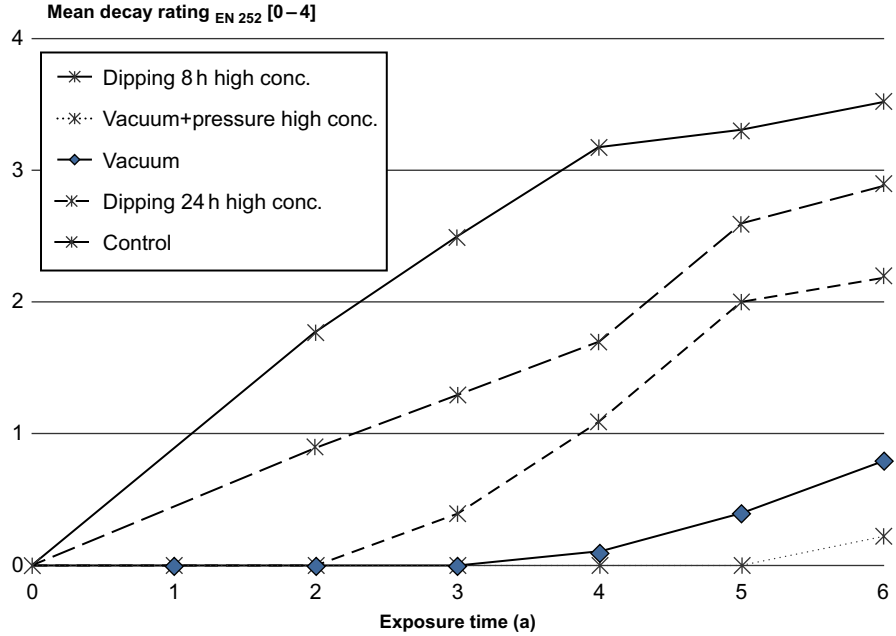


Fig. 4.13 Influence of the impregnation method and respective retentions on performance of copper-amine-treated spruce wood in EN 252 test (Humar *et al.*, 2016a,b).

degraded after six weeks of exposure. Considerable decay was noted on dipped specimens as well. It would seem that the copper shell treatment did not prevent decay but only prolong the lag phase. On the other hand, the first signs of decay were noticed on copper-treated wood after the 6th year (Fig. 4.13).

4.3.5 Conclusions

It is believed that chemical preservation will remain the predominant method for wood protection in Europe in the forthcoming decades. Toxic active ingredients will be replaced with more environmentally acceptable alternatives. It is believed that modified wood will replace wood treated with biocides in less demanding applications when the price for the modified wood will drop. On the other hand, effective alternatives for preservative-treated wood have to be developed.

4.4 Wood modification

S. Bollmus, A. Gellerich, H. Militz
University of Göttingen, Göttingen, Germany

4.4.1 Introduction

In recent years, the requirements on wood preservatives and modification processes have changed. Until the middle of the past century, biocides were mainly used for wood preservation. The agents and formulations used showed a high efficacy and good penetration capability. However, during the last decades, the discussion about health effects and environmental aspects intensified. Therefore, wood protection without biocides increasingly gained importance in Europe as an environmentally friendly method to enhance wood properties, especially the resistance against wood-degrading fungi (Rowell, 1983). Different modification processes are of scientific and economic interest. These processes focus on the improvement of the resistance against wood-decaying fungi and on increased dimensional and weathering stability (Rowell, 2009; Mai, 2010).

The term ‘wood modification’ comprises every method to enhance wood properties during its service life (Hill, 2006). Modified wood should display a higher resistance against wood-decaying fungi whilst being non-toxic. For each modification system, the resistance against wood-decaying fungi increases with the degree of modification (Fig. 4.14).

Wood modification also focuses on improving the dimensional stability of wood (Fig. 4.14). The accuracy of modern construction elements is of central interest, and wood modification could result in a positive influence on cracking performance. This is especially important for wood in outside applications, as cracks can be gateways for moisture and wood-decaying fungi. Furthermore, an improved cracking performance leads to extended service life of coatings and thus to less maintenance schedules of wood products (e.g. windows).

Depending on the modification process, it is possible to influence other wood properties, for example, hardness, strength properties or elasticity.

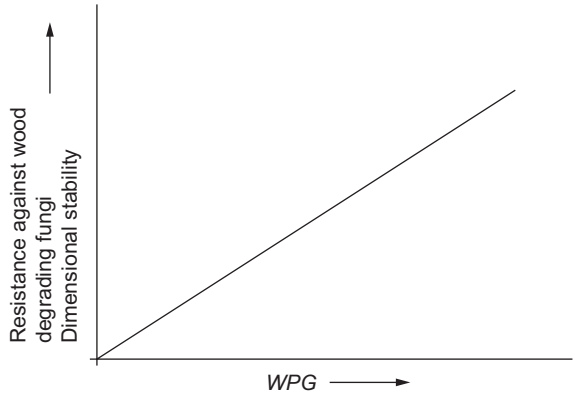


Fig. 4.14 Resistance against wood-degrading fungi and dimensional stability depending on weight percent gain (WPG) (degree of modification).

A distinction is made between thermal and chemical modification processes. During thermal modification processes, the wood is treated at temperatures between 160°C and 240°C, which changes the cell wall components.

Each chemical modification process is based on two stages. In the first stage, the wood is impregnated with a liquid. During the second stage, the modification agent is cured, and the wood is dried. Therefore, the wood species needs to be able to get impregnated, meaning that it must be possible for liquids to penetrate the wood.

The subsequent drying and curing process is a serious challenge. During the impregnation step, the wood exhibits high moisture content. Furthermore, the modification often requires temperatures of above 100°C, which can lead to the risk of cracking or other damages.

Impregnations are carried out in customary vacuum pressure impregnation plants, which are similar to those plants used for pressure impregnations with water-based wood preservatives.

Besides chemical and thermal modification processes, there are modification systems based on waxes, paraffin and oils. Usually, these substances are located in the cell lumen as they are not able to penetrate the cell wall because of their molecular size or polarity.

It should be noted that modification systems usually increase the resistance against wood-decaying fungi, but they are only partly effective against discolouring fungi like blue stain and moulds.

4.4.2 Modification systems

4.4.2.1 Thermal modification

Out of all wood modification processes, thermal modification exhibits the highest economic importance, with some processes already established on the market. All of them utilise the principle that the cell wall components are chemically changed at high temperatures (above 150°C). A multitude of different types of reactions takes place

at these temperatures, for example, hydrolytic splitting of polysaccharides, oxidation and radical reactions and different condensation reactions. Due to the treatment, many different chemical transformations occur during the thermal modification. Within the temperature range usually applied during the processes, hemicelluloses are the first cell wall components that are affected (Militz and Altgen, 2014). Hereby, properties like durability and dimensional stability are positively influenced. However, heat treatment leads to the loss of strength and a dark discolouration due to a partial degradation of cell wall composites. Heat-treated wood is therefore not used for load-bearing components. Main areas of application are claddings, garden timber, deckings and others. Another area of application is interior design, where thermally modified wood is used because of its dark colour.

Thermally modified wood shows a lower density than untreated wood, due to the thermal degradation of cell wall components and the loss of mass during treatment. The durability generally increases with the applied temperature and the exposure period. At the same time, mechanical properties of the wood are reduced. Thus, heat treatment always constitutes a compromise between increased resistance against fungi and decreased strength properties (Leithoff and Peek, 1998; Ewert and Scheiding, 2005; Esteves *et al.*, 2009).

As indicated earlier, thermal modification processing occurred for treatments between 160°C and 240°C (Militz and Altgen, 2014). Besides the temperature, the main differences in the treatments regard the process management or the modification medium. Possible media used are water vapour, nitrogen or vacuum atmospheres and oil.

Whilst most thermally modified softwoods were commercially available during the first years, companies have recently started to look at different hardwoods. Depending on the producer, it is possible to purchase heat-treated beech, poplar, oak or ash for different applications.

4.4.2.2 Treatments with oils and waxes

Treatments using oils, waxes or paraffin lead to storage of the substance within the cell lumen and mostly enhance the hydrophobicity. The hydrophobing agents are not able to change the chemical structure of the cell wall, as they do not form chemical bonds and are mostly located in the cell lumen (Sell, 1977). Storing water-repelling (hydrophobic) substances in the cell lumen may, however, detain moisture from components. Liquid water penetrates the pores of treated wood at a slower rate than those of untreated wood. In addition, gaseous water is absorbed more slowly by oil-treated wood, meaning that the equilibrium moisture content is reached after a longer period of time compared with untreated material.

As treated wood absorbs less water, the variations in moisture between periods with strong solar radiation and periods of high humidity are lower, resulting in decreased cracking being observed.

Repelling water (wood protection by protection against moisture) is generally accepted as a method for improving some of the properties of wood (Borgin, 1965), and treatment with oils and waxes can help such improvement. This is particularly so with wood species that, due to their permeable structure, absorb more water (Sailer, 2000). Undertaking oil and wax treatments can result in performances similar to

low-permeable wood species and improving natural durabilities to levels exhibited naturally by some species (e.g. teak, *Tectona gandis*). However, treatment solely with oils (vegetable oils and mineral oils) does not ensure sufficient long-term protection against wood-decaying fungi in use classes UC 3.2 (permanent moistening) and UC 4 (ground contact).

Treating wood with molten waxes/paraffin is a technical challenge due to their high melting points. In order to introduce the wax deeply into the wooden body, the impregnation needs to be carried out at temperatures above the melting point of the wax. Alternatively, a solution or emulsion might be used, where the waxes are dispersed using an emulsifier (Lesar and Humar, 2011; Humar *et al.*, 2016a). The water absorption of wood might be clearly reduced by filling the cell lumen or by lining the cell walls. Wood modified with waxes, oils or paraffin has been commercially available for some years now in Germany (Dauerholz) and Austria (Natwood), where each producer exclusively treats softwoods with hydrophobing agents.

4.4.2.3 Acetylation

Acetylation is a modification system based on the esterification of acetic anhydride (Hill *et al.*, 1998; Hill, 2006). Acetylated wood is commercially available and has been scientifically and technologically examined for several years (Homan, 2008; Bongers *et al.*, 2010).

Commercially available acetylated wood exhibits a high resistance against wood-decaying fungi. Wood properties like dimensional stability (swelling/shrinkage) and equilibrium moisture content are clearly improved (Rowell, 1983; Militz, 1991).

The commercial process is based on a reaction between the hydroxyl groups on the wood cell wall with acetic anhydride. The reaction results in esterification of the accessible hydroxyl groups in the cell wall with the formation of by-product acetic acid (Hill *et al.*, 1998). Depending on the process, it is possible that small quantities of the acetic acid remain in the wood, which might influence fittings and fasteners negatively. It is consequently important to employ non-corrosive material for fittings, for example, stainless steel.

Acetylated wood is at the moment exclusively produced by Accsys (The Netherlands) and is available under the trade name of Accoya. Until a few years ago, only radiata pine (*Pinus radiata*) was marketed in an acetylated form as, since it showed good results after modification due to anatomical preconditions. During the last couple of years, other wood species have been acetylated, for example, beech (*Fagus sylvatica*). Initial studies have proved to be promising studies, so currently, attempts are being made together with industrial partners to establish these on the market.

4.4.2.4 Treatment with resins

The degree of modification is indicated by the difference of mass before and after modification, as each reactive resin increases the mass. The WPG states how much the mass of the wooden body is increased by modification. Depending on the wood species, resin and application, the WPG of resin-modified wood lies between ~10% and 30%. It is known that dimensional stability and resistance against wood-decaying

fungi and some mechanical properties such as hardness and compression strength are increased with increasing WPG.

According to Stamm and Seborg (1939), three criteria for effective resin treatment of wood are known

- Molecular size—resin molecules need to be small enough to penetrate the cell wall.
- Soluble in polar solvents—resin molecules need to be soluble in polar solvents. That fact will lead to a swollen cell wall, which allows the resin to diffuse into the interior of the cell wall.
- Polarity—resin molecules need to exhibit a sufficient polarity for high affinity to react with cell wall macromolecular components.

Treatments with resins are so-called impregnation modification systems. They are based on the principle that the cell wall is impregnated with a chemical that will be fixed within the cell wall. According to Hill (2006), the following mechanisms affect the properties of modified wood:

- Cell wall bulking (permanent swollen state of cell wall) results in improved dimensional stability of wood.
- Space within the cell wall will be occupied by resin that leads to less space for water molecules. This results in a reduction in hygroscopicity.
- Resin blocks cell wall micropores. This leads to reduction of diffusion of water and other molecules into the cell wall.

4.4.2.5 Furfurylation

Furfurylation is a modification system based on furfuryl alcohol. Furfuryl alcohol is obtained from renewable resources like sugarcane, oat hulls, corncobs, rice or peanut shells and reed. Furfurylated wood shows a clearly increased resistance against wood-decaying fungi and a greatly improved dimensional stability. Moreover, mechanical properties like compression strength or hardness are enhanced (Westin *et al.*, 2004; Lande *et al.*, 2004, 2008; Bollmus *et al.*, 2012).

Initial studies to modify solid timber by furfurylation were conducted during the 1950s (Lande *et al.*, 2008). Since then, different companies have modified wood with different furfurylation processes. Today, furfurylated wood is available by the trade names of Kebony (Norway) and NobelWood (The Netherlands).

The company Kebony mainly furfurylates different species of pine wood. They furfurylate Scots pine (*Pinus sylvestris*), radiata pine (*P. radiata*) and North American pine assortment southern yellow pine.

Furthermore, Kebony treats beech and maple (*Acer* spp.) in small quantities. These products are mainly utilised as deckings. Moreover, modified hardwoods directly compete with tropical wood, based on appearance and properties.

Besides products for exterior use, which is the main area of application, Kebony produces timbers for interior use, such as flooring. The objective of modifying wood for interior use is to increase hardness and dimensional stability. If resistance against fungi is not of major interest, a low degree of modification is sufficient.

In addition to the softwoods radiata pine and southern yellow pine, Kebony furfurylates beech, maple and ash (*Fraxinus excelsior*) for interior use.

The company that produces NobelWood, Foreco (The Netherlands), predominantly uses softwoods to produce furfurylated timber. The main areas of application are claddings and deckings.

4.4.2.6 DMDHEU

1,3-Dimethylol-4,5-dihydroxy-ethyleneurea (*DMDHEU*) is an important finishing chemical for cotton fibres used in manufacturing non-crease textile fabrics. Initial trials were conducted during the 1960s to apply DMDHEU for the modification of wood, since cotton and wood both contain cellulose (Weaver *et al.*, 1960). Since 2003, the DMDHEU treatment of solid wood and veneers has been developed up to pilot scale. Initially, only pine (solid wood) was modified (Krause, 2006; Schaffert, 2006). Later on, extensive studies (Wepner, 2006; Bollmus, 2011) were conducted using beech (solid wood and veneers). The BASF SE started to merchandise this product under the name of 'Belmadur'. Nowadays, TimTech (New Zealand) is producing DMDHEU-treated wood for the domestic and the international market. TimTech modifies radiata pine because of its availability and its easy impregnability. Each product is characterised by high resistance against wood-decaying fungi, a clearly improved dimensional stability and improved bending and compression strength and increased hardness. However, some properties experience a negative influence, probably induced by the catalyst. Impact bending strength and tensile strength of wood modified with DMDHEU are clearly reduced. Furthermore, the treated wood shows a liability of cracking.

Furthermore, the industry is interested in producing and merchandising DMDHEU-treated wood in Germany.

4.4.2.7 Phenol

Phenols were developed more than 100 years ago as a substitute for natural shellac. It is produced from coal tar-phenol and formaldehyde. Worldwide production covers about 5 million t/year with upscale, with temperature-resistant insulating materials for automotive, electrical, and mechanical engineering and aeronautics as the main areas of application.

The wood materials industry primarily uses phenolic resins as binding agents for weather-resistant wood-based products (see Chapter 2). Furthermore, there are several producers of synthetic resin densified wood (e.g. obo-Festholz, Germany; Delignit Panzerholz, Germany; and Pagholz, Germany) who impregnate beech veneers with phenolic resin, which are afterwards pressed under temperature and pressure. These products exhibit a high density (1200–1450 kg/m^3) because of the densification and high WPGs.

Another form of utilisation of phenol comprises its use in chemical wood modification, as studied on scientific level and now being implemented at industrial scale. This process—in contrast to what is done in the synthetic resin densified wood industry—applies phenolic compounds, which are able to penetrate the cell wall similarly to furfuryl alcohol or DMDHEU.

Modification of beech with phenolic resins considerably improves the resistance against wood-decaying fungi (reaching durability class 1–2). This is achieved by a

different protective mechanism; amongst others, the resin stored within the cell wall decreases the accessibility for moisture and for decaying reagents. Moreover, the dimensional stability, hardness and the compression strength of the wood are improved through the treatment. Tensile strength is usually slightly decreased, whilst bending strength and flexural modulus of elasticity remain unaffected or are slightly increased (Furuno *et al.*, 2004; Bicke *et al.*, 2012; Evans *et al.*, 2013).

4.5 Coatings and hydrophobes

M. Petrič
University of Ljubljana, Ljubljana, Slovenia

4.5.1 Introduction—Why surface finishes

The first question that appears when having in mind surface finishes is 'do we really have to treat solid wood, wood-based composites and other bio-based building materials—predominantly lignocellulosics—with surface finishes?' The answer is quite straightforward, no. There are plenty of examples of old wooden buildings all over the world that have never been surface-treated with finishes or coated with film-forming materials, but they are still in a good condition and perfectly well serve their functions. During utilisation, the constructions with bio-based materials are exposed to abiotic and/or biotic harmful influences of specific exposure conditions. However, when they are properly designed in order to avoid or minimise the risk of their damages, deterioration, decay, etc., there is not really a need to apply surface-finishing materials to ensure the expected service life.

Nevertheless, people frequently decide for surface treatment of building materials, because they want to change their natural appearance. In such a case, aesthetic function of a finish is the only or the main one when someone decides to utilise a surface finish. This brings us to the general conclusion that the expected function of a finish—either protective or aesthetic or both—is the decisive factor in the coating selection process. Both elements, aesthetics and protection, can sometimes be at odds with each other (Daniel *et al.*, 2004). Aesthetically, there is a growing trend amongst homeowners to maintain the natural look of the wood's original colour. However, the best protection from the sun's ultraviolet radiation is obtained from pigmented products, which tend to cover the wood's natural grain and texture (Daniel *et al.*, 2004).

Of course, there are elements in buildings that are not exposed to weathering, but if we subtract surface-finished furniture, only a few of them are expected to be coated: the examples are wooden flooring, wooden stairs and maybe also interior wall claddings. Usually, such elements are coated largely due to aesthetic reasons and only in some cases because of protection against abiotic factors like wear or liquids (for instance, in the case of wooden stairs or flooring). On the other hand, protection of bio-based building materials in exterior use is a much higher challenge, and therefore, the focus of this chapter is on coatings and other surface treatment materials in outdoor exposure.

4.5.2 Surface finishing materials

A definition of the term 'coating material' is given by the standard ISO 4618 (ISO, 2014) 'Paints and varnishes—Terms and definitions, 'a product, in liquid, in paste or powder form, that, when applied to a substrate, forms a film-possessing protective, decorative and/or other specific properties' (Bulian and Graystone, 2009). According to Bulian and Graystone (2009), from this definition, two aspects can be considered: (1) a coating material produces a protective and decorative film. Films may be unpigmented and transparent or opaque. The essential nature of the product depends on the component that forms a continuous film. (2) The coating material will be applied to a substrate before forming a film. This process can be done only if the coating material is at a certain stage in a liquid form. The transition from liquid to solid is a fundamental step to the formulation, manufacture, application and behaviour of coating materials. In addition, there are also some other film non-forming surface-finishing materials, like bleaches, stains and water repellents (hydrophobisation agents).

Coatings (and the materials that do not form a film) are usually very complex formulations, consisting of non-volatile and volatile matter. The main component of non-volatile matter is a film-former or a binder, and the others may be pigments, dyes, fillers and all kinds of additives, like hardening accelerators, thickeners, dispersants, flow control agents, preservatives and UV-protecting agents. Volatile matter consists of solvents or dispersants and thinners and some volatile additives (Brock *et al.*, 2000). Taking into account the required function of a surface treatment material, its complex composition, predicted application process and the foreseen curing or drying procedure, it has to be highlighted that nothing such as a universal surface treatment material exists—or, if it does, this is usually only a poor solution.

4.5.3 Classification of surface finishing products

There exist numerous classification systems for surface-finishing products. They may be divided according to the film-forming binder (e.g. to polyacrylate, alkyd, polyurethane, polyester, etc. finishes), on the basis of the application process (for spraying, curtain coating, roller coating, etc.), according to the drying/curing procedure, by intended use and their functions (for interior or outdoor applications), film thickness, their appearance (opaque or transparent, with a high or low gloss), etc. (Jaić and Živanović-Trbojević, 2000). In terms of their environmental profile—that is on the basis of the volatile matter type, we can distinguish between solvent-borne and water-borne coatings. Bulian and Graystone (2009) mention the categorisation of the finishes with a relevance to the end use sector. So, they write about decorative (or architectural) and industrial coatings, finishes for joinery and windows and for furniture and coatings for parquet and wood flooring. In another chapter of their book, Bulian and Graystone (2009) proposed several classification categories, and when a generic type is considered, they proposed the following classes, paints (opaque systems that hide wood's texture), clear and semitransparent coatings (varnishes and lacquers), stains and lasure and oils, polishes and patinas.

For the matter of simplicity, surface treatment materials herein are elaborated in categories similar to those mentioned by Bulian and Graystone (2009): pigmented

paints, clear and semitransparent finishes, natural oils, and wetting—hydrophobisation agents that do not form films on a material's surface. As mentioned, the focus is on finishes for exterior applications. Within each category, some selected, the most relevant properties are described, which largely relate also to finishes from other classes.

4.5.3.1 Pigmented paints

Pigmented paints to be used outdoors are usually based on alkyd binders. These are the binders most greatly used in paints since the obtained product is both economical and versatile (Ambrosi and Offredi, 1996). Traditionally, (high gloss) paints were part of a three-product system comprising primer, undercoat and a top (gloss) layer (Bulian and Graystone, 2009). Many of new paints are two-product or one-product multicoat systems. In the majority of cases, various kinds of alkyd polymers are used as a binder. Because of environmental requirements, traditional solvent-borne alkyd paints are less frequently used, and the content of volatile organic compounds (VOCs) in solvents and thinners has been lowered by the introduction of high solid alkyds or water-soluble or emulsified alkyds (Bulian and Graystone, 2009). Nevertheless, acrylic opaque water-borne paints are also used, as noted by De Windt *et al.* (2014). As explained by De Meijer (2001), the protective function of a coating in exterior wood applications can be split up into the following parts: protection against the uptake of moisture and the related dimensional changes, protection against photochemical degradation of the wood surface and prevention of microbiological degradation by blue-stain and mould fungi. In terms of weathering of pigmented opaque paints with a high hiding power, the damage of wood beneath the paint layers is not the problem, because of the reflective and absorption properties of the pigments. A wide range of pigments may be used. The most important inorganic ones are TiO_2, ZnO, ZnS, lithopones (produced by precipitating $BaSO_4$ and ZnS together), iron oxide pigments, chromium and cadmium-based pigments, etc. The organic ones are carbon black, azo and polycyclic pigments, metal complex pigments and many others (Brock *et al.*, 2000). It should be noted that paints (also semitransparent finishes) contain more or less harmful/toxic elements, and this means that painted wood and bio-based materials at the end of their service life can often may not be regarded as an environmentally benign material.

Nevertheless, the paints themselves are susceptible to weathering; as evident by colour changes and/or the loss of gloss, erosion and cracks may appear, with spots originating from blue stain, and, finally, deeper cracks also in the wooden substrate and flaking (detachment) of the coating system (De Windt *et al.*, 2014). Concerning the paint, it was shown that the degradation of the acrylic resin in the opaque paint during weathering is very important (Landry and Blanchet, 2012). De Windt *et al.* (2014) observed the significant influence of substrate texture on the coating performance and stressed the need to evaluate the wood/coating system in total. In fact, this generalisation is widely accepted: one has always to regard a substrate and a finish as a unity—as a surface system. In terms of this statement, Bonura *et al.* (2004) listed a long list of factors that need to be considered if one wants to achieve the optimum coating performance. These are proper building design, the optimal selection of wood type, correct preparation of the substrate including the right moisture content, the selection of the correct primer and topcoat, proper high-quality applicator and

application method should be used, and finally, maintenance should be performed on time and appropriately.

The colour of the paint for exterior applications should be considered as well (Ambrosi and Offredi, 1996). It is known that dark colours absorb a greater quantity of radiations and that therefore become more heated. Degradation processes are faster at higher temperatures, so when a paint with a high hiding powder is selected, the best decision is to apply a white paint and the worst colour is the black one.

One of the most important factor influencing on durability of coated systems is dimensional instability of a substrate due to moisture uptake and release. Therefore, in the following section, moisture transport through a coating system is described in more detail.

4.5.3.2 *Coating permeability and wood moisture content in service*

There is a clear link between coating permeability and moisture levels in the substrate. As reported by Miller (2005), the solvent-borne paint system tested provided an effective barrier to water penetration, in that there was no measurable change in moisture content during the one week absorption and desorption cycle. Coatings that are more permeable permitted moisture contents to rise to values exceeding 20% during the 7-day test, and significant increases in moisture content were recorded 10 mm below the coated surface. Of particular concern was the observation for permeable coatings that on cessation of wetting and commencement of the drying phase; the moisture front initially advanced deeper into the wood.

The influence of a coating on the moisture absorption of wood was studied for instance by Van Mell *et al.* (2011). They found out that the alkyd coating inhibited moisture absorption of the woods studied. This coating hardly absorbed any water and sealed the rays. Consequently, it formed an effective barrier against moisture. In the case of the acrylic coating, the wood type was of a great influence on the moisture absorption. The coating thickness had no significant effect on the water uptake. On pine, the acrylic coating sealed the relatively large rays, thereby reducing the absorption of unbound water by ~40%–50%. However, as in the case with meranti (*Shorea* spp.), the acrylic coating did not prevent water uptake of the cell walls. With spruce, the acrylic coating almost completely inhibited water absorption, by cell walls, lumina and rays. This was most likely the result of fixation of aspirated pits near the surface by coating constituents. To conclude, the water absorption of the studied uncoated wood samples is dominated either by diffusion (hardwood meranti) or by capillary uptake (softwoods pine and spruce). In the case of diffusion-dominated absorption, the water uptake of the applied coating determines the water uptake of the wood (high/low uptake of acrylic/alkyd coating results in high/low uptake of meranti). In the case of capillary-dominated absorption, a film-forming coating (alkyd or acrylic) seals the capillaries (rays and lumina). The absorption is largely determined by diffusion and therefore dependent on the water uptake of the coating. Sivertsen and Flaete (2012) confirmed the statement that the surface system and not just a coating type must also be considered. The larger permeability of the water-borne topcoat had a larger effect on the high-density spruce specimens than on low-density spruce. This illustrates that different wood substrates can lead to different results in tests on coating performance.

What is better—low or higher permeability of a coating? It has been shown that when the weather is changing fast (shorter periods of heavy rain and humidity and relatively fast alterations between warm/hot and cool/cold weather periods), higher coating permeability is an advantage: Dimensional changes are higher, but on the other hand, wood is allowed to dry during warm and dry periods. On the other hand, when the building material is used in a climate with long highly humid conditions, it is better to seal the substrate with non-permeable coating, in order to prevent fungal decay due to longer periods of exposure of lignocellulosic material above 20% relative moisture content. However, trapped water under such a finish may cause delamination of the coating systems during hot and dry periods (because of a high partial water pressure in wood). For example, it was evidenced (Grüll and Anderl, 2004) that coatings can promote the accumulation of moisture at the exterior side of the wooden profile. On the other hand, permeable finishes (very often acrylic waterbornes) may be susceptible to blue-stain infestations (Fig. 4.15). Therefore, as a rule, water-borne finishes for exterior use contain fungicides, like IPBC and/or isothiazolinones. To sum up, what kind of a coating to be chosen in terms of its permeability very much depends on specific exposure conditions.

Finally, when speaking of a surface system instead of the coating one, one should bear in mind that the substrate might be pretreated with a biocide-containing formulation. Therefore, for example, Pavlič *et al.* (2005) studied the performance of exterior coatings on spruce wood treated with the alkanolamine-boric acid complex and stated it was different than on non-treated wood. Drying of coatings on impregnated wood was most likely changed because of boron diffusion into the coating layers during the drying process. Slower drying resulted in stickier films. Adhesion of coating on pretreated wood was not decreased; in one case, even an increase was indicated. Permeability of a wood-coating system was also influenced by the pretreatment of wood with a new boron-based biocide. The increase of permeability was more evident on the acrylic coating.

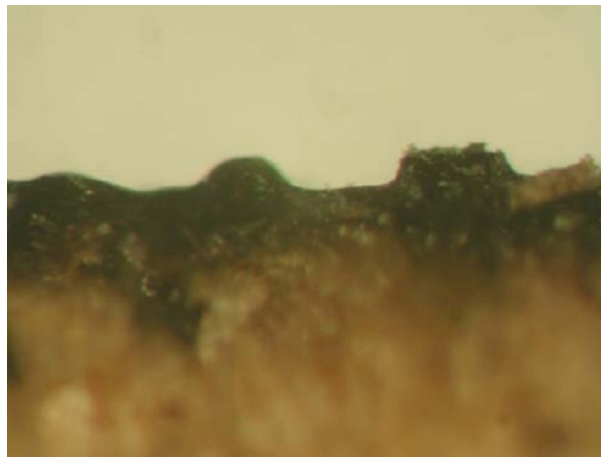


Fig. 4.15 Protuberances on the acrylic coating after exposure to blue-stain fungi (88×).

However, De Meijer and Nienhuis (2009) showed that not only the coating permeability should be taken into account but also the moisture-related swelling of the coating is also important. The swelling of the coating is preferably in the same range as that of wood but can never be equal due to differences in swelling caused by differences within growth rings and anatomical directions of the wood.

4.5.3.3 Semitransparent and transparent finishes

A wide variety of semitransparent or transparent finishes and stains can be applied on bio-based substrates. When considering the resistance of coated materials against weathering, there is quite a different situation to opaque paints described previously. Here, it is not only (or predominantly) water that may have a negative influence on the surface system's durability. UV rays from solar irradiation may have detrimental effects on a finish and on a substrate in a relatively short period. First, in contrast to opaque paints, a dark colour of a finish is preferred, absorbing some UV and majority of visible light, which also causes damage (Ambrosi and Offredi, 1996). Secondly and especially when a light coloured or even colourless clear coat is desired, highly efficient UV-protective additives are obligatory.

Archetypal stains are designed to penetrate and will generally have a relatively low volume solids content (Bulian and Graystone, 2009). Penetration of a coating into the substrate is important, since it provides good and sufficient mechanical anchoring, promoting the adhesion strength and improving the cohesive strength of the wood surface. Penetration also reduces the stress gradient transition between the coating and the substrate with an improvement of mechanical properties (Bulian and Graystone, 2009). According to Bulian and Graystone (2009), another similar class of finishes consists of varnishes and other clear coats. A clear coat—the one that forms a solid transparent film, is more general then the term ‘varnish’. This theoretically refers to a clear coat drying by oxidation. Traditional exterior varnish application has quite declined in favour of wood stains, due to high incidence of flaking and discolouration (Bulian and Graystone, 2009). Such finishes become brittle with ageing, due to depolymerisation of binders and subsequent and uncontrolled cross-linking of depolymerisation fragments.

Overall, in order to overcome the problems related to unwanted effects of UV (and visible) light, UV-protective methods must be applied.

4.5.3.4 How to increase resistance of a semitransparent or transparent finish and wood beneath against UV light

The first possibility has already been mentioned in the chapter on opaque paints: the weathering performance of stains and clear coats can be improved by various pigments. Nevertheless, this is the solution only in the case of semitransparent finishes. In addition, classical pigments in coatings, together with commonly used additives for the UV protection of wood (UV absorbers and light stabilisers—radical scavengers), change the natural appearance of wood and make a finish often not fully transparent. It was shown that some nanoparticles, for example, nano-sized ZnO, show an excellent ultraviolet and infrared absorption and a high transparency in the visible range

(Weichelt *et al.*, 2011). It is generally accepted that the transparency of nanocomposite is not affected by incorporating nanoparticles in the polymer matrix (Salla *et al.*, 2012 and references therein). At an optimum particle size of 2–50 nm, visible light will be transmitted, and the system becomes essentially translucent (Allen *et al.*, 2002). Apart from nano-ZnO (Salla *et al.*, 2012), nanoparticles of TiO_2 (Cristea *et al.*, 2011; Pori *et al.*, 2016; Godnjavec *et al.*, 2012) are frequently used, along with many others, for example, CeO_2 (Lu *et al.*, 2014). It is important to note that the nanoparticles can be embedded in a coating, or they can be deposited onto the wood's surface (TiO_2, Fig. 4.16), as can CeO_2 (Lu *et al.*, 2014).

More convenient than the nano-sized UV-protective agents are UV absorbers, light stabilisers and antioxidants (George *et al.*, 2005). UV absorbers act by selective absorption of UV radiation between 290 and 400 nm, preventing the photoactivation of UV-sensitive groups in the coating binder and in the surface layer of the underlying wood. UV absorbers therefore protect the deeper coating layers and the wood/coating interfaces. The main effects are protection against coating and substrate discolouration, against blistering, flaking and peeling and even against the loss of gloss and cracking of the topcoats (George *et al.*, 2005). The most common organic UV absorbers are based on triazole chemistry, such as benzotriazole (Mahltig *et al.*, 2005). The other protective additives are radical scavengers, and amongst them, the most known is *HALS*—hindered amine light stabilisers. HALS, in the primer, help to inhibit the photooxidation of lignin and binders by trapping the free radicals. It maintains the mechanical properties of the wood surface and contributes to better retention of coating/substrate adhesion. HALS are effective against loss of coating surface properties such as gloss, microcracking of clear coats and surface erosion (George *et al.*, 2005). The radical trapping additives can be also antioxidants (George *et al.*, 2005).

Possible mechanisms of UV protection of the system '(semi)transparent coating—wood' are schematically presented in Fig. 4.17. UV (and visible) light may be reflected

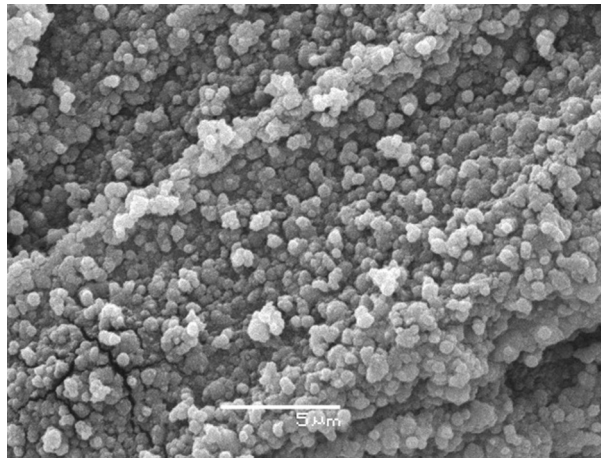


Fig. 4.16 Particles of TiO_2 deposited on a surface of wood by a low-temperature hydrothermal process.

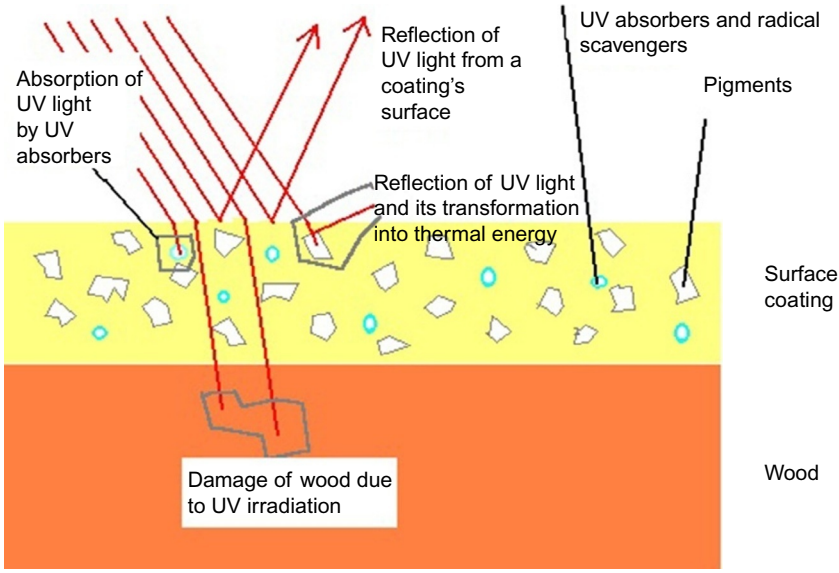


Fig. 4.17 Schematic presentation of protection mechanisms of the system '(semi)transparent finish/substrate' against UV (and also visible) light.

from a coating's surface. Some radiation may penetrate into a coating and cause its photodegradation and may also penetrate into wood (or other lignocellulosic materials) and cause its damage. If there are pigments (also nano-sized) present, they can reflect some of unwanted light, or they can absorb the light and convert it into less harmful heat. Free radicals, formed in the coating by UV light may be trapped by radical scavengers, if present, and transformed into non-harmful chemical compounds. The net effect of this process is again transformation of harmful energy of UV rays into thermal energy. UV absorbers and radical scavengers transfer UV energy into the thermal one in cyclic processes, which means that they may perform their function for several years. However, they are also degraded by weathering and can be leached out from a finish, so maintenance is needed from time to time, typically in about 5 years. Maintenance intervals are largely dependent on specific exposure conditions (climate, precipitation rate, temperatures, annual energy of solar irradiation, etc.)

4.5.3.5 Natural oil based finishes

On the market, there is an increased demand for bioproducts, with naturally protected surfaces (Kärki, 2000). Why there is such a large interest on natural surface finishes (like natural drying oils) for wood? What are their advantages? First of all, it has been well documented long ago (Howard *et al.*,1998; Fortmann *et al.*, 1998) that various furniture paints and varnishes with synthetic binders may represent a significant source of VOCs indoors and this problem may be reduced by using 'natural' furniture finishes (Weissenfeld, 1988). More generally, increased production and use of natural surface coatings are caused by general public interest on environmental issues (European Commission, 1999).

Controlling moisture content is a very effective way of protecting timber against biotic degradation factors because treating with biodegradable oil, like tall oil, reduces the capillary water uptake of wood (Gonzales Laredo *et al.*, 2015). Vegetable oils may be potential preservatives when applied as a layer into wood surface by decreasing water absorption and actually performing as water repellents.

In terms of the most frequently used natural oils, the majority of studies and products to date have focused on natural drying (and semidrying oils) and specifically linseed oil, tung oil, castor oil and hemp oil.

Natural drying and semidrying oils are liquid vegetable (or fish) oils that react with oxygen to form solid films (Brock *et al.*, 2000; Wicks *et al.*, 1999). They are triesters of glycerol and fatty acids. Their reactivity with oxygen results from the presence of diallylic groups or conjugated double bonds. The most frequently used drying oils for surface treatment are linseed, tung, dehydrated castor oil, hemp oil and various fish oils, and the most important semidrying oils are soya bean, safflower and sunflower oil (Brock *et al.*, 2000). In general, according to Weissenfeld (1988), oils can be used as natural, environment friendly surface finishes.

Linseed oil, obtained from seeds of *Linum usitatissimum*, is one of the most important and well-known natural oils for surface treatment of wood. It is a non-conjugated drying oil, containing 52% of linolenic acid and 16% of linoleic acid, 22% of oleic acid (Fig. 4.18A–C) and 10% of saturated fatty acids (Wicks *et al.*, 1999). It dries relatively slowly, and it is therefore often used in a modified form, called boiled oil, obtained by heating of raw linseed oil with the addition of drying agents. However, linseed oil is most frequently applied as a medium for manufactured trade oils and varnishes. Raw linseed oil finishes require constant reoiling due to their short-lived enhancing effect (Leach, 1993).

Tung oil contains about 80% of conjugated α-eleostearic acid (Fig. 4.18D) and consequently dries relatively fast (Wicks *et al.*, 1999). It is resistant to alkalis and water and mostly used in combination with resins for water-resisting varnishes (Leach, 1993). Tung oil is a very popular finish, probably because it is very easy to repair.

A major component (87%) of a *natural castor oil* is ricinoleic acid (Fig. 4.18E) with only one double bond, so it is a non-drying oil. Its derivative, a *dehydrated castor oil*, dries relatively rapidly at room temperature, but on further exposure to air, the surface becomes tacky (Wicks *et al.*, 1999). Therefore, it is mostly used in formulations together with resins (Leach, 1993).

A drying *hemp oil* from seeds of *Cannabis sativa* contains up to 70% of linoleic acid and in combination with a linseed oil gives somewhat softer finishes resistant against weathering (Herer, 1994).

4.5.3.6 Hydrophobisation agents

At first, it should be clarified what are the purposes of biomaterial treatment with hydrophobisation formulations, especially because there is not a direct link between hydrophobic properties of a finish and an equilibrium moisture content in wood and other lignocellulosic materials. As already mentioned, water repellents decrease capillary uptake of water, and therefore, the wetted hydrophobic substrate is most probably

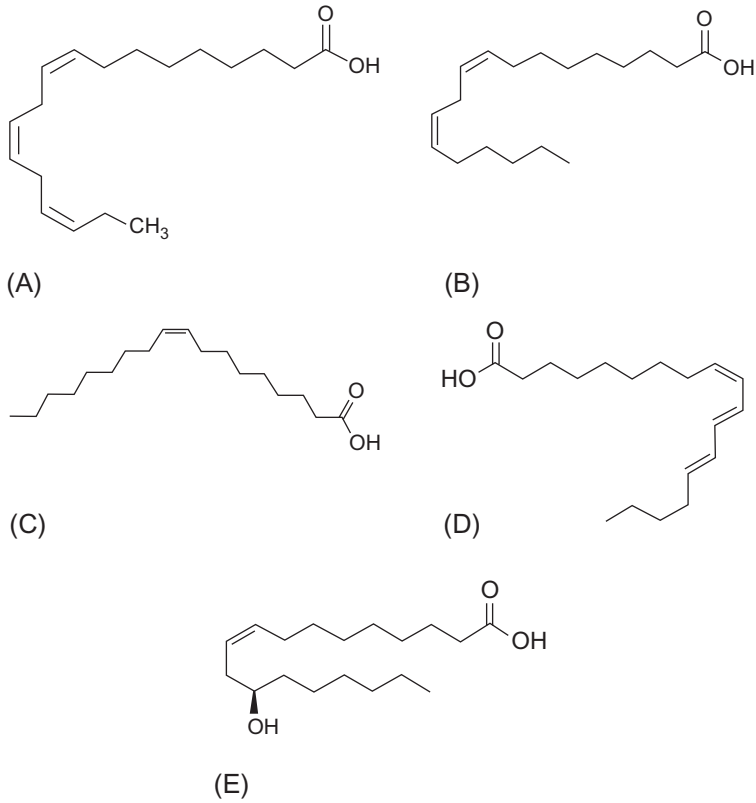


Fig. 4.18 Examples of some components of drying oils: (A) linolenic acid, (B) linoleic acid, (C) oleic acid, (D) α-eleostearic acid and (E) ricinoleic acid.

dried faster than the untreated one. This is especially important in terms of prevention of fungal decay. For instance, it was shown (Humar and Lesar, 2013) that wood treated with hydrophobic tung oil and linseed oil was protected against brown- and white-rot fungi. Further on, hydrophobic treatment (like with montan wax) may reduce leaching of leachable biocides from a substrate, thus improving performance of such a preservative (Lesar *et al.*, 2009). In addition, it was also evidenced that treatment of wood with waxes, as the most typical and common water repellents, slows photodegradation of wood (Lesar *et al.*, 2011) and most likely also other lignocellulosic or biomaterials.

Waxes are the most conventional hydrophobisation agents. Wax is defined as any of a class of pliable substances of natural or synthetic origin that differs from fats in being less greasy, harder and more brittle. In principle, waxes contain compounds of high molecular weight (like esters, fatty acids, alcohols and saturated hydrocarbons) (Encyclopaedia Britannica, 2000). The term wax was originally applied to naturally occurring vegetable, animal and mineral substances, chemically defined as esters of fatty acids and certain monohydric alcohols, other than glycerol. The fatty acids found in animal and vegetable waxes are almost always saturated (Encyclopaedia Britannica, 2000; Brock *et al.*, 2000). Most commonly used natural waxes for wood

finishes are beeswax and carnauba wax, but very often, synthetic paraffin wax is applied to cheaper, conventional furniture (Weissenfeld, 1988). Other natural waxes that might find application in surface finishing of wood are woollen wax, candelilla wax, berry wax, etc. (Leach, 1993). Beeswax is secreted by worker bees. It is soft to brittle, and it consists mainly of free cerotic acid and myricyl palmitate. It ranges from yellow to almost black in colour, depending on factors as the age and diet of the bees (Encyclopaedia Britannica, 2000). It is non-toxic and one of the most important waxes used for finishing of indoor furniture, wooden flooring and wooden toys. It can be applied in pure state or in mixtures with other waxes, oils, resins and solvents. The ratio between the wax, oils and solvents determines the hardness of a finish (Leach, 1993; Weissenfeld, 1988). Another very important wax for surface finishing of wood is carnauba wax. This is a vegetable wax harvested from leaves of the palm tree (*Copernicia cerifera*), growing in Brazil. It is one of the hardest waxes and can be combined with other waxes to give harder and less sticky surfaces (Leach, 1993). It is also often mixed with various oils.

Apart from classical hydrophobisation agents like waxes, many other water-repellent materials and hydrophobisation processes (not presented in this chapter) appeared (Petrič, 2013). For instance, hydrophilic surface of wood can be converted into a hydrophobic one by the method of grafting, for instance, of methyl methacrylate onto the wood surface (Olsson *et al.*, 2012). A frequent way of hydrophobisation of wood surfaces was reported to be a covalent grafting of silicone compounds (Sebe and Brook, 2001), and silane-based sol-gel coatings can also be applied for the same purpose (Wang *et al.*, 2011). Manoudis *et al.* (2008) presented a simple, low-cost strategy for the production of superhydrophobic surfaces that can be applied on large surfaces (e.g. buildings). Polymer particle dispersion was sprayed on a substrate, also wood, and this process could result in the formation of a rough two-length-scale hierarchical structure that exhibited water-repellent properties. Permanent hydrophobisation of wood surfaces was obtained by covalent attachment of fluoroorganyl substituents to wood hydroxyl groups via benzotriazolyl-activated, substituted benzoic acid (Drafz *et al.*, 2012). An example of wood hydrophobisation with ionic liquids can also be found in literature. Kot and Kowaluk (2010) covered surfaces of beech wood with ammonium ionic liquid and achieved long-lasting hydrophobic and antiseptic properties.

Currently, superhydrophobicity is in the focus of surface-related phenomena investigations, as shown by Carre and Mittal (2009). A superhydrophobic surface is the one having a high water contact angle (>150 degree), low contact angle hysteresis and low sliding angle (<10 degree) (Zhu *et al.*, 2014). This type of surface can be made by depositing a hydrophobic material onto a surface with nanoroughness or producing nanoroughness on a hydrophobic material, having prospective applications for self-cleaning, ice accumulation prevention, antifouling, anticorrosion, non-sticking, drag reducing, etc. (Zhu *et al.*, 2014). Just as an example of the state of the art in the field, Tu *et al.* (2016) prepared superhydrophobic coatings on wood: mechanically robust superhydrophobic surfaces were fabricated on naturally microgrooved wood based on a two-step process, that is, first, applying a primer coating of transparent epoxy resin to cover the surface microstructures, followed by construction of superhydrophobic films using silica/epoxy resin/fluorinated alkylsilane nanocomposites.

4.5.4 Maintenance

As already mentioned, the focus of this section has been on wood finishes for outdoor applications. Therefore, in this short chapter about maintenance, the focus is also on the maintenance of exterior surface wood finishes.

It is not only bio-based material substrate, such as wood, that is prone to degradation due to weathering but also the coating systems themselves, since they undergo degradation caused by several weathering factors. UV light and moisture are harmful for binder polymers of coatings, and long-term exposure leads to increasing brittleness, chalking, cracking and flaking. The dimensional movement, cracking and surface degradation of the wood substrate also negatively influence coating durability (Grüll *et al.*, 2011). As written by Grüll *et al.* (2011), maintenance is vital to retain the integrity of the coating film and prolongs its service life.

When is the right time to apply a maintenance of a coating before weathering leads to defects that would require renovation? There has been little work published discussing maintenance of surface-finished bio-based materials, including wood, in detail. The exception is the mentioned paper of Grüll *et al.* (2011), where the authors investigated maintenance procedures of different wood-coating systems and tried to get experience on the proper time intervals for maintenance. It was found that the opaque white coating systems were the most durable ones reaching long intervals of required maintenance (for comparison, see some thoughts about the colour of a coating in Sections 4.5.3.1 and 4.5.3.3). For systems with lower durability on the maintained surfaces, further degradation of the coatings was prevented, whilst the surfaces without maintenance showed marked alterations in the following six months of exposure. Different characteristics were observed for film-forming and non-film-forming semitransparent varnishes where surface degradation was uniform without local discolouration or flaking but many cracks in the wood surfaces with the non-film-forming systems.

4.6 Protection by design and maintenance

C. Brischke[*,†], *M. Humar*[‡], *D. Lorenzo*[§]
[*]Leibniz University Hannover, Hannover, Germany
[†]University of Göttingen, Göttingen, Germany
[‡]University of Ljubljana, Ljubljana, Slovenia
[§]University of Santiago de Compostela, Lugo, Spain

4.6.1 Principles

Organic building materials that are generally susceptible to degradation by various biotic agents can be simply protected by assuring that either decay organisms have no access or physical prerequisites for such organisms are inhibited. This means moisture, temperature and oxygen level are kept below minimum or above maximum for activity or even survival of the respective organisms.

In a broader sense, the choice of materials, for example, wood species of different durability for differently severe exposure conditions, can also be considered as part of the design process and therefore being ‘protection by design’. Purpose-related selection of building materials, the use of building components in adequate dimension and the consideration of physical properties such as the anisotropic deformation of timber due to swelling and shrinking should be part of the building conception (conceptual protection).

During the construction process, usually differently skilled groups are working not only subsequently but also partly in parallel on the same structure. This requires exchange of relevant information and careful definition of working tasks to avoid work execution mistakes due to misunderstandings between acting persons. In particular, sensitive building materials such as insulation materials and components foreseen for indoor use require protection from the weather also during the building phase (Fig. 4.19).

Usually, protection by design is used synonymously with ‘moisture protection’ to avoid any moisture-induced risk for decay or any other kind of biotic attack. Hereby, two principle rules are followed: (1) keeping water away from the structure and, if this is not possible, (2) removing water from the structure as fast and as effective as possible. It is agreed in general that biocidal treatment is applied for wood only, if wood cannot be protected by construction measures.

Besides numerous design solutions, water can be kept away from organic building material by application of coatings and covers (physical protection). Coatings have long been used efficiently for moisture protection of timber products such as window joinery or claddings. However, their efficacy strongly depends on their own robustness and climate. As soon as a coating becomes defective, its protective character can turn into the opposite since defective coatings act as water traps. For example,

Fig. 4.19 Organisational protection of building materials and components during the construction phase. Left, building in Aquitaine, France, from construction site with still open roof. Right, open wood roof with vapour barrier (foil) not yet covered by slate boards.

thick organic coatings were found very effective in the United Kingdom and Northern Europe. On the other hand, in much warmer and sunny Southern Europe, they were found considerably less efficient.

Furthermore, coating and covers can be used as mechanical barriers to restrict accessibility of an organic substrate for insects or marine borers. In particular, metal and polymer wraps are used for this purpose. However, performance of coatings is described in detail in Section 4.5.

4.6.2 Moisture protection

The majority of organic building materials are susceptible to moisture, and wetting is a prerequisite for biotic decay. Hence, moisture protection is a key issue for any bio-based building material. Keeping water away from the structure is the first and most important step in any protection concept by design. Moisture can derive from rain, hail or snow—in combination with wind considered as wind driven rain (WDR). Furthermore, it derives from air humidity, and water vapour can condensate indoors, outdoors and most critically within the building envelope where redrying is usually inhibited. Finally, rising water can derive from the soil or any other porous fundament.

Good and bad practise examples in Figs 4.20–4.36 illustrate the potential to protect components made from bio-based building materials from wetting.

If water uptake is unavoidable or the respective protective measures do not coincide with the overall design concept, other measures need to be taken to assure fast redrying, that is, drainage and ventilation measures. This can be achieved through declined horizontal surfaces as shown in Fig. 4.37.

Fig. 4.20 Ventilation measures—avoiding direct contact with wet walls. Left, end of beam in direct contact with wet wall. Right, physical separation between end of beam and wet wall that allows drying of wood.

Fig. 4.21 Ventilation measures—avoiding water traps. Left, water trapping due to direct contact between metal support and laminated. Right, physical separation between wood and wall that allows ventilation to protect the joint area.

Fig. 4.22 Protection from wind-driven rain through roof overhangs. Left, indoor part of a wall without eave. Right, building in north Spain with sufficiently wide roof overhang to keep away driving rain from the exterior wall.

Fig. 4.23 End grain protection from wind-driven rain. Left, end grain beam unsealed without protection and decay consequences. Right, correct detail design in a building in rainy north of Spain with physical end grain protection against driving rain.

Fig. 4.24 Effect of shelter. Left, moistening of an exterior wall due to splash as consequence of a lacking of gutter. Right, perfect facade design in west France, with cascaded eaves that avoid accumulation of water from driving rain. Sufficient slope of the roof assures water draining and prevents water ingress through the roofing and the facade.

Fig. 4.25 Protection of windows by design. Left, exterior wooden window gallery without physical protection and wetting is the consequence. Right, window with rain protection board.

Fig. 4.26 Protection from splash water. Left, exterior wooden door without any splash protection. Right, exterior wood door in Paris, France, with bottom part covered with metal sheet to avoid the splash on the wooden part of the door.

Fig. 4.27 Protection from splash water. Left, wetting of cladding made from thermally modified wood in north Spain due to splash water—growth of moulds and disfiguring fungi. Right, cladding in north Spain with correct detail design to avoid splash water.

Fig. 4.28 End grain protection. Left, timber bridge in Spain without end grain protection of severely decayed main beam. Right, end grain metal covers of projecting exterior beams.

Fig. 4.29 Effect of covers. Left, main truss of timber bridge in Spain without physical protection in top board, water accumulation and severe decay. Right, pedestrian bridge in Lugo, Spain, physical protection against driven rain on top of main beam.

Fig. 4.30 Protection from water accumulation. Left, decking with no correct design due to contact board to board. Right, decking well designed thanks to a good separation between boards that avoid water accumulations.

Fig. 4.31 End grain cover. Left, end grain of fence post with cracks and decay. Right, wooden cover board on column.

Fig. 4.32 Effect of covers. Left, end grain joint on railing without cover protection. Right, fence post with traditional copper cover to protect joint area.

Fig. 4.33 Protection from ground contact. Left, pedestrian bridge with main beam wood in direct contact with ground. Right, pedestrian bridge in Galicia, Spain, *green circle* indicating separation of load-bearing trusses from ground.

Fig. 4.34 Protection from ground contact. Left, pedestrian bridge with pillars in direct contact with ground. Right, pedestrian bridge in Galicia, Spain, with concrete fundaments and load-bearing pillars separated from the ground.

Fig. 4.35 Protection from ground contact. Left, pedestrian bridge with pillars in direct contact with ground. Right, separation of timber elements from ground.

Fig. 4.36 If steel anchors are not applied correctly, their effect can turn into the opposite direction. Left spruce wood pillar on steel anchor in Arboretum in Kamnik, Slovenia. Right, part of the children playground in Mali Lošinj, Croatia.

Fig. 4.37 Water draining and avoidance of water trapping. Left, decking with good details design to allow dripping rainwater and space between two boards to avoid water accumulations. Right, hand rail in Kristineberg, Sweden: Declined surface but gap between two elements with potential for water trapping.

4.6.3 Physical barriers against termites, beetle larvae and marine borers

In the case of subterranean termites, which can become a significant problem in Southern European countries, physical barriers can be a suitable solution to avoid the entrance of these insects in the interior of buildings and to avoid from direct contact to wood and wood-based products used for indoor commodities. Subterranean termites live and create their nests in ground, and from there, they attack wood elements in ground contact (UC 4), above ground contact (UC 3) and indoor conditions (uses class 1 and 2). For the latter, physical barriers against termites are considered as a promising system to avoid their entrance into the interior of buildings through flooring or exterior walls.

There are two main physical barriers against termites, plastic barriers (Fig. 4.38) and steel nets (Fig. 4.39). Similar barriers are used for the marine borers as well (Figs 4.40 and 4.41).

Fig. 4.38 Physical barriers against termites. Left, wooden flooring in ground floor inside a building in Spain without any physical termite barrier and severe degradations by termites. Right, building under construction in France and blue physical termite barrier.

Fig. 4.39 Physical barriers against termites. Left, ground floor in wood inside a building in Spain in direct ground contact and severe degradations by subterranean termites. Right, steel net used to avoid the entrance of subterranean termites inside a building.

Fig. 4.40 Physical barriers against marine borers. Left: Copper-treated pine wood bridge pillar in saltwater contact (UC 5) in Spain with several marine borer degradations. Right: Physical barrier marine borer test in Spain.

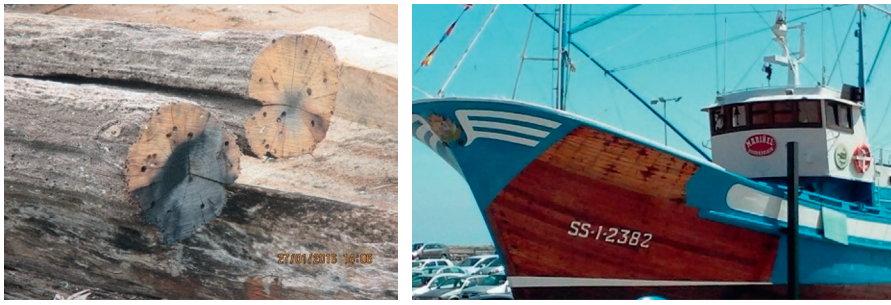


Fig. 4.41 Physical barriers against marine borers. Left, eucalyptus beams punt in sea salt water contact (UC 5) in Spain with several marine borer degradations. Right, painting barrier in a ship against marine borers in Spain.

4.6.4 Quantifying the effect of protective measures

Performance-based design requires quantification of decay-influencing factors even more than prediction of absolute service lives in years. As expressed through the factor method according to ISO 15686-1 (ISO, 2011), a global approach is needed to quantitatively consider all internal and external factors that might affect the performance of a commodity or structure. Factorisation based on a reference commodity exposed to reference conditions has therefore become a preferential method for design and planning (MacKenzie *et al.*, 2007; Thelandersson *et al.*, 2011; Isaksson and Thelandersson,

2013; Isaksson *et al.*, 2014). Nevertheless, factorisation can also be considered as a probabilistic process, and accurate models are needed to determine factors for specific parameters. The quantification of various decay-influencing factors has therefore been addressed in several studies (e.g. Brischke *et al.*, 2013; Isaksson and Thelandersson, 2013; Isaksson *et al.*, 2013; Bornemann *et al.*, 2014; Brischke and Meyer-Veltrup, 2015) and is shown exemplarily in the following.

Ideally, the effect of a certain parameter on the resulting service life of a wooden structure should be determined. This is, to some extent, intended by different standard durability test methods (e.g. EN 252, CEN, 2015b), when, for example, the service lives of test specimens exposed in ground are determined and compared with those of reference materials, such as non-durable sapwood controls. However, for more durable materials or if the material is exposed to a less severe environment, the determination of service lives can take many years or even decades. Alternatively, the dose needed before decay occurs and thus leading to a certain lifetime can serve as an alternative measure for quantitative factorisation of service-life-affecting influences. Different measures describing the effect of decay factors such as the number of wet days, temperature- and moisture-induced dose and the resulting predicted service life were therefore compared. After at least 3 years of outdoor exposure, the moisture risk was assessed for different test specimens, combined facade deck elements exposed to south and north, fence and terrace elements and fence posts with differently detailed post caps and bearings (e.g. Bornemann *et al.*, 2014).

In summary, such prediction models showed high potential to save time when monitoring timber products exposed outdoors, particularly under less severe conditions such as vertically mounted cladding. Differences between wood species and between design details became apparent. More simple measures such as the number of wet days (here defined as days with MC > 25%) did not meet the expectation to the same extent but can still be considered as useful alternative indicators. The results of several studies recommend taking more advantage of the additional information provided by continuous MC measurements, particularly for service life and performance prediction. Similar perceptions have been observed by Brischke *et al.* (2014) in a survey amongst European scientists working in the field of wood protection and technology.

Exemplarily, the quantification of sheltering effects through roof overhangs is illustrated in Fig. 4.42. Based on long-term measurements, the moisture-induced risk was assessed for three different eaves at different heights on a Norway spruce cladding in Taastrup, Denmark. For simple utilisation in performance-based design, one can estimate the expected dose from the ratio between eave and distance to the roof edge.

More recently, there were several European research projects elaborating design guidelines based on factorisation such as WoodExter (Thelandersson *et al.*, 2011), WoodBuild (Isaksson *et al.*, 2014) and the still running WoodWisdom-Net project durable timber bridges (*DuraTB*, e.g. Niklewski *et al.*, 2016). Their overall aim was to quantify in a comprehensive manner the effect of the different decay-influencing factors in a precise way but implement them in a design guidance concept that allows easy application to the user.

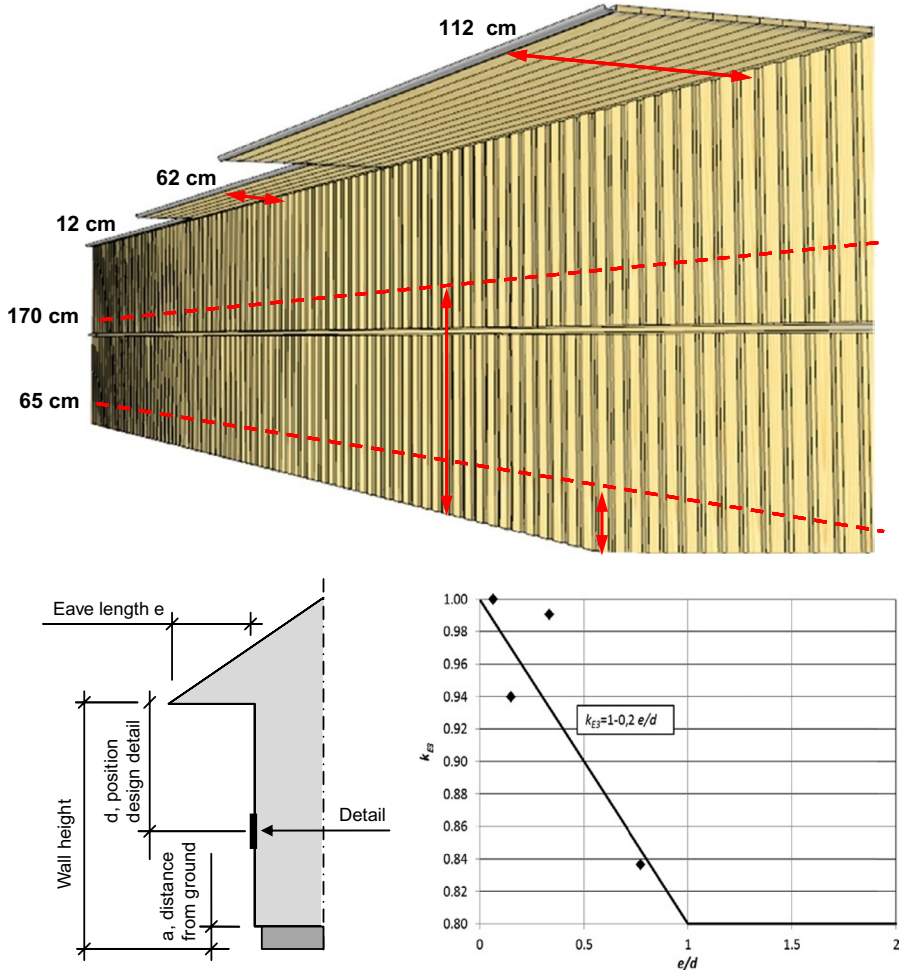


Fig. 4.42 Quantifying the effect of eaves on the moisture-induced decay risk. Top, board-on-board cladding with different eaves monitored for several years in Taastrup, Denmark. Bottom, relation between the ratio *e*/*d* and the total dose based on measured *T* and MC expressed as factor k_{E3} according to Isaksson *et al.* (2014).

References

Allen, N.S., Edge, M., Ortega, A., Liauw, C.M., Stratton, J., McIntyre, R.B., 2002. Behaviour of nanoparticle (ultrafine) titanium dioxide pigments and stabilisers on the photooxydative stability of water based acrylic and isocyanate based acrylic coatings. Polym. Degrad. Stab. 78, 467–478.

Ambrosi, P., Offredi, P., 1996. The Painter's Manual. A Guide to Professional Wood Painting. HBpi.erre Editrice, Milan.

Appelqvist, C., Havenhand, J.N., Toth, G.B., 2015. Distribution and abundance of teredinid recruits along the Swedish coast—are shipworms invading the Baltic Sea? J. Mar. Biol. Assoc. U. K. 95, 783–790.

Bauch, J., 1984. Development and characteristics of discolored wood. IAWA Bull. 5, 91–98.

Bicke, S., Mai, C., Militz, H., 2012. Modification of beech veneers with low molecular weight phenol formaldehyde for the production of plywood: durability and mechanical properties. In: Proceedings of the European Conference on Wood Modification, Ljubljana, Slovenia.

Blanchette, R.A., 2000. A review of microbial deterioration found in archaeological wood from different environments. Int. Biodeterior. Biodegrad. 46, 189–204.

Bollmus, S., 2011. Biologische und technologische Eigenschaften von Buchenholz nach einer Modifizierung mit 1,3-dimethylol-4-5-dihydroxyethyleneurea (DMDHEU) (PhD Thesis). Georg-August-Universität Göttingen.

Bollmus, S., Treu, A., Westin, M., Brynildsen, P., Militz, H., 2012. Use of furfurylated wood for the production of windows—results from the WinFur project. In: Proceedings of the European Conference on Wood Modification, Ljubljana, Slovenia.

Bongers, F., Alexander, J., Jorissen, A., Blaß, H.J., Hill, C.A.S., 2010. Acetylated wood in structural applications. In: Proceedings of the European Conference on Wood Modification, Riga, Latvia.

Bonura, T., Bussjeager, S., Christensen, L., Daisey, G., Daniels, T., Hirsch, M., Jourdain, C.J., Douglas Mall Sr., D., Springate, B., Wagner, L.E., Warren, H., Williams, R.S., 2004. Finishes Checklist. A guide to achieving optimum coating performance on exterior wood surfaces. JCT. CoatingsTech. 1 (3), 42–48.

Borges, L.M.S., 2014. Biodegradation of wood exposed in the marine environment: Evaluation of the hazard posed by marine wood-borers in fifteen European sites. Int. Biodeterior. Biodegrad. 96, 97–104.

Borges, L.M.S., Merckelbach, L.M., Cragg, S.M., 2014a. Biogeography of wood-boring crustaceans (*Isopoda: Limnoriidae*) established in European coastal waters. PLoS One 9. e109593.

Borges, L.M.S., Merckelbach, L.M., Sampaio, Í., Cragg, S.M., 2014b. Diversity, environmental requirements, and biogeography of bivalve wood-borers (Teredinidae) in European coastal waters. Front. Zool. 11, 1–13.

Borgin, K., 1965. The Testing and Evaluation of Water Repellents. BWPA Annual Convention, Stratford. pp. 67–84.

Bornemann, T., Brischke, C., Alfredsen, G., 2014. Decay of wooden commodities—moisture risk analysis, service life prediction and performance assessments in the field. Wood Mater. Sci. Eng. 9, 144–155.

Brischke, C., Meyer-Veltrup, L., 2015. Moisture content and decay of differently sized wooden components during 5 years of outdoor exposure. Eur. J. Wood Wood Prod. 73, 719–728.

Brischke, C., Rapp, A.O., Bayerbach, R., 2006. Decay influencing factors: a basis for service life prediction of wood and wood-based products. Eur. J. Wood Wood Prod. 1, 91–107.

Brischke, C., Meyer, L., Bornemann, T., Bilstein, M., Lauenstein, B., Lück, J.-M., Wulf, C., 2013. Service life of timber structures—prognosis based on three years high-frequency monitoring. Eur. J. Wood Wood Prod. 71, 79–90.

Brischke, C., Meyer, L., Suttie, E., 2014. Towards performance based durability standards for wood in construction—part 2: considering moisture risks in wooden components. In: Quattrone, M., John, V.M. (Eds.), Proceedings of XIII International Conference on Durability of Building Materials and Components, 02–05th September 2014, Sao Paulo, Brazil, pp. 65–72.

Brock, T., Groteklaes, M., Mischke, P., 2000. European Coatings Handbook. Vincentz Verlag, Hannover.

Bulian, F., Graystone, J.A., 2009. Wood Coatings: Theory and Practice. Elsevier, Amsterdam, Oxford.

Carre, A., Mittal, K.L., 2009. Superhydrophobic Surfaces. VSP/Brill, Leiden.

CEN, 1994. EN 350-2:1994. Durability of Wood and Wood Based Products—Natural Durability of Solid Wood—Be Part 2: Guide to Natural Durability and Treatability of Selected Wood Species of Importance in Europe. European Committee for Standardization, Brussels, Belgium.

CEN, 1996. EN 113:1996. Wood Preservatives—Method of Test for Determining the Protective Effectiveness Against Wood Destroying Basidiomycetes—Determination of the Toxic Values. European Committee for Standardization, Brussels, Belgium.

CEN, 2007. EN 351-1:2007. Durability of Wood and Wood Based Products—Preservative-Treated Solid Wood—Part 1: Classification of Preservative Penetration and Retention. European Committee for Standardization, Brussels, Belgium.

CEN, 2010–12. EN 1995-1-1:2010–12. Eurocode 5: Design of Timber Structures—Part 1-1: General—Common Rules and Rules for Buildings. European Committee for Standardization, Brussels, Belgium.

CEN, 2013. EN 335:2013. Durability of Wood and Wood-Based Products—Use Classes: Definitions, Application to Solid Wood and Wood-Based Products. European Committee for Standardization, Brussels, Belgium.

CEN, 2015a. CEN/TS 15083-1:2015. Durability of Wood and Wood-Based Products—Determination of the Natural Durability of Solid Wood Against Wood-Destroying Fungi. Test Methods—Part 1: Basidiomycetes. European Committee for Standardization, Brussels, Belgium.

CEN, 2015b. EN 252:2015. Field Test Method for Determining the Relative Protective Effectiveness of a Wood Preservative in Ground Contact. European Committee for Standardization, Brussels, Belgium.

Connell, M., 2004. Issues facing preservative suppliers in a changing market for treated wood. In: Final Workshop COST Action E22, Environmental Optimisation of Wood Protection, Lisboa, Portugal, 22nd–23rd March 2004. 8 p, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.424.3629&rep=rep1&type=pdf.

Cristea, M.V., Riedl, B., Blanchett, P., 2011. Effect of addition of nanosized UV absorbers on the physico-mechanical and thermal properties of an exterior waterborne stain for wood. Prog. Org. Coat. 72, 755–762.

Daniel, G., Nilsson, T., 1998. Developments in the study of soft rot and bacterial decay. In: Bruce, A., Palfreyman, J.W. (Eds.), Forest Products Biotechnology. Taylor and Francis, London, 326 p.

Daniel, T., Hirsch, M.S., McClelland, K., Ross, A.S., Williams, R.S., 2004. Clear exterior finishes: finding the balance between aesthetics and durability. JCT. Coatings Tech. 1 (9), 36–49.

De Meijer, M., 2001. Review on the durability of exterior wood coatings with reduced VOC-content. Prog. Org. Coat. 43, 217–225.

De Meijer, M., Nienhuis, J., 2009. Influence of internal stress and extensibility on the exterior durability of wood coatings. Prog. Org. Coat. 65, 498–503.

De Windt, I., Van de Bulcke, J., Wuijtens, I., Coppens, H., Van Acker, J., 2014. Outdoor weathering performance parameters of exterior wood coating systems on tropical hardwood substrates. Eur. J. Wood Wood Prod. 72, 261–272.

DIN, 2007. DIN 68811:2007. Imprägnierung von Eisenbahnschwellen aus Holz mit Kreosot (Steinkohlenteeröl) (Impregnation of Wood Railway Sleepers With Creosote {Coal Tar Based Oils}). DIN Deutsches Institut für Normung e. V., Beuth Verlag GmbH, Berlin.

Drafz, M.H.H., Dahle, S., Maus-Friedrichs, W., Namyslo, J.C., Kaufmann, D.E., 2012. Chemical improvement of surfaces. Part 2: Permanent hydrophobization of wood by covalently bonded fluoroorganyl substituents. Holzforschung 66, 727–733.

Eaton, R.A., Hale, M.D., 1993. Wood: Decay, Pests and Protection. Chapman and Hall Ltd, London.

Encyclopaedia Britannica, 2000. Wax. http://www.britannica.com (29.8.2000).

ENV, 2001. ENV 807:2001. Wood Preservatives. Determination of the Effectiveness Against Soft Rotting Micro-Fungi and Other Soil Inhabiting Micro-Organisms.

Esteves, B.M., Pereira, H., Helena, M., 2009. Wood modification by heat treatment: a review. Bioresources 4 (1), 370–404.

European Commission, 1999. Memorandum of Understanding for the Implementation of a European Concerted Research Action Designated as COST Action E18 "High Performance Wood Coating". European Commission, Brussels.

Evans, P., Gibson, S.K., Cullis, I., Liu, C.L., Sebe, G., 2013. Photostabilisation of wood using low molecular weight phenol formaldehyde resin and hindered amine light stabilizer. Polym. Degrad. Stab. 98 (1), 158–168.

Ewert, M., Scheiding, W., 2005. Thermoholz in der Anwendung. Eigenschaften und Möglichkeiten. Holztechnologie 1, 22–29.

Fortmann, R., Roache, N., Chang, J.C.S., Guo, Z., 1998. Characterization of emissions of volatile organic compounds from interior alkyd paint. J. Air Waste Manag. Assoc. 48, 931–940.

Furuno, T., Imamura, Y., Kajita, H., 2004. The modification of wood by treatment with low molecular weight phenol-formaldehyde resin: a properties enhancement with neutralized phenolic-resin and resin penetration into cell walls. Wood Sci. Technol. 37 (5), 349–361.

George, B., Suttie, E., Merlin, A., Deglise, X., 2005. Photodegradation and photostabilisation of wood—the state of the art. Polym. Degrad. Stab. 88, 268–274.

Godnjavec, J., Znoj, B., Veronovski, N., Venturini, P., 2012. Polyhedral oligomeric silsesquioxanes as titanium dioxide surface modifiers for transparent acrylic UV blocking hybrid coating. Prog. Org. Coat. 74, 654–659.

Gonzales Laredo, R.F., Rosales-Castro, M., Rocha-Guzman, N.E., Gallegos-Infante, J.A., Rocio Moreno-Jimenez, M., Karchesy, J.J., 2015. Wood preservation using natural products. Madera Bosques 21, 63–76.

Greaves, H., 1971. The bacterial factor in wood decay. Wood Sci. Technol. 5, 6–16.

Grüll, G., Anderl, T., 2004. Wood moisture content of coated wood/aluminum windows. Part 2: Reactions to interior humidity stress. Surf. Coating Int. B Coating Trans. 87 (B), 149–234.

Grüll, G., Truskaller, M., Podgorski, L., Bollmus, S., Tscherne, F., 2011. Maintenance procedures and definition of limit states for exterior wood coatings. Eur. J. Wood Wood Prod. 69, 443–450.

Herer, J., 1994. Die Wiederentdeckung der Nutzpflanze Hanf (Cannabis Marihuana). Zweitausendeins, Frankfurt.

Hill, C.A.S., 2006. Wood Modification: Chemical, Thermal and Other Processes. John Wiley & Sons, Chichester.

Hill, C.A.S., Jones, D., Strickland, G., Cetin, N.S., 1998. Kinetic and mechanistic aspects of the acetylation of wood with acetic anhydride. Holzforschung 52 (6), 623–629.

Homan, W.J., 2008. Development of commercial wood preservatives—efficacy, environmental and health issues. In: ACS Symposium Series, vol. 982. American Chemical Society, Washington, DC.

Howard, E.M., Mccrillis, R.C., Krebs, K.A., Fortman, R., Lao, H.C., Guo, Z., 1998. Indoor emissions from conversion varnishes. J. Air Waste Manag. Assoc. 48, 924–930.

Huckfeldt, T., Schmidt, O., 2006. Hausfäule- und Bauholzpilze – Diagnose und Sanierung. Rudolf Müller, Cologne.

Humar, M., Lesar, B., 2013. Efficacy of linseed- and tung-oil-treated wood against wood-decay fungi and water uptake. Int. Biodeterior. Biodegrad. 85, 223–227.

Humar, M., Thaler, N., 2017. Performance of copper treated utility poles and posts used in service for several years. Int. Biodeterior. Biodegrad. 116, 219–226.

Humar, M., Kržišnik, D., Lesar, B., Thaler, N., Ugovšek, A., Zupančič, K., Žlahtič, M., 2016. Thermal modification of wax-impregnated wood to enhance its physical, mechanical, and biological properties. Holzforschung (in press).

Humar, M., Lesar, B., Thaler, N., Kržišnik, D., Žlahtič, M., 2016b. Influence of the retention and penetration of Cu based preservatives on the performance of softwoods in ground. In: De Troya, T. (Ed.), Designing With Bio-Based Building Materials—Challenges and Opportunities. National Institute for Agricultural and Food Research and Technology, Madrid, pp. 61–62.

Isaksson, T., Thelandersson, S., 2013. Experimental investigation on the effect of detail design on wood moisture content in outdoor above ground applications. Build. Environ. 59, 239–249.

Isaksson, T., Brischke, C., Thelandersson, S., 2013. Development of decay performance models for outdoor timber structures. Mater. Struct. 46, 1209–1225.

Isaksson, T., Thelandersson, S., Jermer, J., Brischke, C., 2014. Beständighet för utomhusträ ovan mark. Guide för utformning och materialval. Rapport TVBK-3066. Division of Structural Engineering, Lund University, Lund.

ISO, 2011. ISO 15686-1:2011. Buildings and Constructed Assets—Service Life Planning—Part 1: General Principles and Framework. International Standardization Organisation, Geneva, Switzerland.

ISO, 2014. ISO 4618:2014. Paints and Varnishes—Terms and Definitions. International Standardization Organisation, Geneva, Switzerland.

Jaić, M., Živanović-Trbojević, R., 2000. Površinska obrada drveta. Teorijske osnove. Tehnološki procesi. Milan Jaić, Belgrade.

Kärki, T., 2000. Species, furniture type, and market factors influencing furniture sales in southern Germany. For. Prod. J. 50, 85–90.

Kim, Y.S., Singh, A.P., 2000. Micromorphological characteristics of wood biodegradation in wet environments: a review. IAWA J. 21, 135–155.

Kleist, G., Schmitt, U., 2001. Characterisation of a soft rot-like decay pattern caused by Coniophora puteana (Schum.) Karst. in Sapelli wood (Entandrophragma cylindricum Sprague). Holzforschung 55, 573–578.

Koch, G., Bauch, J., Puls, J., Welling, J., 2002. Ursachen und wirtschaftliche Bedeutung von Holzverfärbungen. Allg. Forstztg. 57, 315–318.

Kot, M., Kowaluk, G., 2010. Wood hydrophobization by ammonium ionic liquids. Drewno 53, 77–81.

Krause, A., 2006. Holzmodifizierung mit N-Methylolvernetzern (PhD Thesis). Georg-August-Universität Göttingen.

Kretschmar, E.I., Gelbrich, J., Militz, H., Lamersdorf, N., 2008. Studying bacterial wood decay under low oxygen conditions—results of microcosm experiments. Int. Biodeterior. Biodegrad. 61, 69–84.

Kutnik, M., Suttie, E., Brischke, C., 2014. European standards on durability and performance of wood and wood-based products—trends and challenges. Wood Mater. Sci. Eng. 9, 122–133.

Lande, S., Westin, M., Schneider, M., 2004. Properties of furfurylated wood. Scand. J. For. Res. 19, 22–30.

Lande, S., Eikenes, M., Westin, M., Schneider, M., 2008. Furfurylation of wood: chemistry, properties and commercialization. In: Development of Commercial Wood Preservatives. ACS Symp. Ser., vol. 982, pp. 337–355.
Landry, V., Blanchet, P., 2012. Weathering resistance of opaque PVDF-acrylic coatings applied on wood substrates. Prog. Org. Coat. 75, 494–501.
Leach, N.J., 1993. Modern Wood Finishing Techniques. Stobard Davis, Hartford.
Leithoff, H., Peek, R.D., 1998. Hitzebehandlung – eine Alternative zum chemischen Holzschutz? DGfH Holzschutztagung Rosenheim, Germany. Proceedings.
Leppäkoski, E., Gollasch, S., Gruszka, P., Ojaveer, H., Olenin, S., Panov, V., 2002. The Baltic a sea of invaders. Can. J. Fish. Aquat. Sci. 59, 1175–1188.
Lesar, B., Humar, M., 2011. Use of wax emulsions for improvement of wood durability and sorption properties. Eur. J. Wood Wood Prod. 69, 231–238.
Lesar, B., Kralj, P., Humar, M., 2009. Montan wax improves performance of boron-based wood preservatives. Int. Biodeterior. Biodegrad. 63, 306–310.
Lesar, B., Pavlič, M., Petrič, M., Sever Škapin, A., Humar, M., 2011. Wax treatment of wood slows photodegradation. Polym. Degrad. Stab. 96, 1271–1278.
Liese, W., Gröger, C., 1954. Holzschutz. VEB Verlag Technik, Berlin. 140 S.
Lu, Y., Xiao, S., Gao, R., Li, J., Sun, Q., 2014. Improved weathering performance and wettability of wood protected by CeO_2 coating deposited onto the surface. Holzforschung 68, 345–351.
MacKenzie, C.E., Wang, C.-H., Leicester, R.H., Foliente, G.C., Nguyen, M.N., 2007. Timber Service Life Guide. Forest and Wood Products Limited, Melbourne.
Mahltig, B., Böttcher, H., Rauch, K., Dieckmann, U., Nitsche, R., Fritz, T., 2005. Optimized UV protecting coatings by combination of organic and inorganic UV absorbers. Thin Solid Films 485, 108–114.
Mai, C., 2010. Prozesse der chemischen Holzmodifizierung – Stand der industriellen Entwicklung. Holztechnologie 51 (5), 21–26.
Manoudis, P.N., Karapanagiotis, I., Tsakalof, A., Zuburtikudis, I., Panayiotou, C., 2008. Superhydrophobic composite films produced on various substrates. Langmuir 24, 11225–11232.
Melcher, E., Müller, J., 2016. Bewitterung vermeiden. Bauen mit Holz Heft 3, 26–29.
Melcher, E., Zwiefelhofer, J., 2013. Investigations concerning liquid absorption of six heartwood species. Document No. IRG/WP 13-40618. International Research Group on Wood Protection, Stockholm.
Meyer, L., Brischke, C., 2015. Fungal decay at different moisture levels of selected European-grown wood species. Int. Biodeterior. Biodegrad. 103, 23–29.
Militz, H., 1991. Improvements of stability and durability of beechwood (*Fagus sylvatica*) by means of treatment with acetic anhydride. In: Proceedings IRG Annual Meeting, IRG/WP 91-3645. International Research Group on Wood Protection, Stockholm.
Militz, H., Altgen, M., 2014. Deterioration and protection of sustainable biomaterials. In: ACS Symposium Series, vol. 1158. American Chemical Society, Washington, DC.
Miller, E.R., 2005. Wood substrate—the foundation. Surf. Coating Int. B Coating Trans. 88, 157–230.
Nicholas, D.D., Siau, J.F., 1973. Factors influencing the treatability of wood. In: Nicholas, D.D. (Ed.), Wood Deterioration and Its Prevention by Preservative Treatments Volume II Preservatives and Preservative Systems. Syracuse University Press, Syracuse, pp. 299–343.
Niklewski, J., Fredriksson, M., Isaksson, T., 2016. Moisture content prediction of rain-exposed wood: test and evaluation of a simple numerical model for durability applications. Build. Environ. 97, 126–136.

Olsson, S., Johansson, M., Westin, M., Östmark, E., 2012. Grafting of 2-hydroxy-4(2, 3-epoxypropoxy)-benzophenone and epoxidized soybean oil to wood: reaction conditions and effects on the color stability of Scots pine. Polym. Degrad. Stab. 97, 1779–1786.

Palma, P., 2005. Monitoring of shipwreck sites. Int. J. Naut. Archaeol. 34, 323–331.

Pavlič, M., Kričej, B., Tomažič, M., Petrič, M., 2005. Influence of biocide pre-treatment of wood on performance of exterior coatings. Surf. Coating Int. B Coating Trans. 88 (B), 1–82.

Petrič, M., 2013. Surface modification of wood: a critical review. Rev. Adhes. Adhes. 1, 216–247.

Pori, P., Vilčnik, A., Petrič, M., Sever Škapin, A., Mihelčič, M., Šurca Vuk, A., Novak, U., Orel, B., 2016. Structural studies of TiO_2/wood coatings prepared by hydrothermal deposition of rutile particles from $TiCl_4$ aqueous solutions on spruce (*Picea abies*) wood. Appl. Surf. Sci. 372, 125–138.

Råberg, U., Brischke, C., Rapp, A.O., Högberg, N.O., Land, C.J., 2007. External and internal fungal flora of pine sapwood (*Pinus sylvestris* L.) specimens in above-ground field tests at six different sites in south-west Germany. Holzforschung 61, 104–111.

Rademacher, P., Hapla, F., Leder, B., 2010. Untersuchungen zur Holzkonservierung durch Lagerung von Fichtenstämmen unter Folie-Teil I: Zeitreihenmessungen von Klima-und Umweltparametern des gelagerten Holzes. Forstarchiv 82, 3–9.

Rayner, A.D., Boddy, L., 1988. Fungal Decomposition of Wood: Its Biology and Ecology. John Wiley & Sons Ltd, Hoboken, NJ.

Regulation (EU) No. 528/2012 of the European Parliament and of the Council of 22 May 2012 concerning the making available on the market and use of biocidal products. Off. J. L. 167/1.

Rowell, R.M., 1983. Chemical modification of wood. For. Prod. J. 6 (12), 363–381.

Rowell, R.M., 2009. Chemical modification of wood: a short review. Wood Mater. Sci. Eng. 1 (1), 29–33.

Sailer, M., 2000. Anwendungen von Pflanzenölimprägnierungen zum Schutz von Holz im Außenbereich. Dissertation, Universität Hamburg.

Salla, J., Pandey, K.K., Srinivas, K., 2012. Improvement of UV resistance of wood surfaces by using ZnO nanoparticles. Polym. Degrad. Stab. 97, 592–596.

Schaffert, S., 2006. Steuerung und Optimierung von Holzvernetzungsprozessen (PhD Thesis). Georg-August-Universität Göttingen.

Schmid, R., Liese, W., 1966. Elektronenmikroskopische Beobachtungen an Hyphen von Holzpilzen. Supplement 1 Material und Organismen, 251–261.

Schmidt, O., 2006. Wood and Tree Fungi—Biology, Damage, Protection, and Use. Springer, Berlin.

Schmidt, O., Liese, W., 1994. Occurrence and significance of bacteria in wood. Holzforschung 48, 271–278.

Schwarze, F.W., Engels, J., Mattheck, C., 2013. Fungal Strategies of Wood Decay in Trees. Springer, Berlin, Heidelberg.

Sebe, G., Brook, M.A., 2001. Hydrophobization of wood surfaces: covalent grafting of silicone polymers. Wood Sci. Technol. 35, 269–282.

Sell, J., 1977. Hydrophobierende Holzimprägnierung – Wirkweise, Eigenschaften Anwendungsmöglichkeiten. Holz Roh Werkst. 35, 75–78.

Sivertsen, M.S., Flaete, P.O., 2012. Water absorption in coated Norway spruce (*Picea abies*) cladding boards. Eur. J. Wood Wood Prod. 70, 307–317.

Slevin, C., Westin, M., Lande, S., Cragg, S.M., 2015. Laboratory and marine trials of resistance of furfurylated wood to marine borers. In: Proceedings of the Eighth European Conference on Wood Modification, Helsinki, Finland, pp. 464–471.

Stamm, A.J., Seborg, R.M., 1939. Resin-treated plywood. Ind. Eng. Chem. 31 (7), 897–902.
Stienen, T., Schmidt, O., Huckfeldt, T., 2014. Wood decay by indoor basidiomycetes at different moisture and temperature. Holzforschung 68, 9–15.
Thelandersson, T., Isaksson, T., Suttie, E., Frühwald, E., Toratti, T., Grüll, G., Viitanen, H., Jermer, J., 2011. Quantitative design guideline for wood outdoors above ground applications. Document No. IRG/WP 11-20468. International Research Group on Wood Protection, Stockholm.
Tu, K., Wang, X., Kong, L., Chang, H., Liu, J., 2016. Fabrication of robust, damage-tolerant superhydrophobic coatings on naturally micro-grooved wood surfaces. RSC Adv. 6, 701–707.
Unger, W., Unger, A., 1986. Was sind Anobien? Holztechnologie 27, 255–257.
Unger, A., Schniewind, A.P., Unger, W., 2001. Conservation of Wood Artefacts. A Handbook. Springer, Berlin.
Van Mell, P.A., Erich, S.R.J., Huinink, H.P., Kopinga, K., de Jong, J., Adan, O.C.G., 2011. Moisture transport in coated wood. Prog. Org. Coat. 72, 686–694.
Wang, S., Mahlbergb, R., Jämsä, S., Nikkola, J., Mannila, J., Ritschkoff, A.C., Peltonen, J., 2011. Surface properties and moisture behaviour of pine and heat-treated spruce modified with alkoxysilanes by sol–gel process. Prog. Org. Coat. 71, 274–282.
Weaver, J.W., Nielson, J.F., Golstein, I.S., 1960. Dimensional stabilization of wood with aldehydes & related compounds. For. Prod. J. 10 (6), 306–310.
Weichelt, F., Beyer, M., Emmler, R., Flyunt, R., Beyer, E., Buchmeister, M., 2011. Zinc oxide based coatings for the UV-protection of wood for outdoor applications. Macromol. Symp. 301, 23–30.
Weissenfeld, P., 1988. Holzschutz ohne Gift? Ökobuch, Staufen bei Freiburg.
Wepner, F. 2006. Entwicklung eines Modifizierungsverfahrens für Buchenfurniere (*Fagus sylvatica* L.) auf Basis von zyklischen N-Methylol-Verbindungen (PhD Thesis). Georg-August-Universität Göttingen.
Westin, M., Lande, S., Schneider, M., 2004. Wood furfurylation process and properties of furfurylated wood. In: Proceedings IRG Annual Meeting IRG/WP04-40289.
Wicks Jr., Z.W., Jones, F.N., Pappas, S.P., 1999. Organic Coatings: Science and Technology. Wiley-Interscience, New York, NY.
Wilcox, W.W., 1978. Review of literature on the effects of early stages of decay on wood strength. Wood Fiber 9, 252–257.
Willeitner, H., 2001. Current national approaches to defining retentions in use. COST E22, Brussel. 8 p.
Winandy, J.E., Morrell, J.J., 1993. Relationship between incipient decay, strength, and chemical composition of Douglas-fir heartwood. Wood Fiber Sci. 25, 278–288.
Zhu, M., Rong, M.Z., Zhang, M.Q., 2014. Self-healing polymeric materials towards non-structural recovery of functional properties. Polym. Int. 63, 1741–1749.
Zink, P., Fengel, D., 1989. Studies on the coloring matter of blue-stain fungi. Holzforschung 43, 371–374.

This page intentionally left blank

Performance of the bio-based materials

5

5.1 Introduction

C. Brischke[*,†], *M. Humar*[‡]
*Leibniz University Hannover, Hannover, Germany
[†]University of Göttingen, Göttingen, Germany
[‡]University of Ljubljana, Ljubljana, Slovenia

It is generally agreed that wood can be a high-performing material, but sometimes, there is a great misunderstanding what the term performance is referring to. What is performance? Performance is a rather frequently used term, but there are several explanations for this word. There are almost 10,000 scientific articles published, describing various performances of wood and other bio-based building materials, and the purpose of the respective manuscript is to analyse, condensate and summarise them.

In general, performance is described as the capabilities necessary for a material to demonstrate minimum requirements, and to satisfy the criteria of respective standard or user expectations. User expectations open a great variety of properties, resolving the most important: function, aesthetics, durability, moisture dynamics, thermal properties, and fire resistance. It is very unlikely that one material fulfils all expectations of users; hence, we have to focus on where wood and other bio-based materials perform the best and can compete with other man-made materials. Unfortunately, performance data for many wood-based building materials and suitable comprehensive test methodologies to determine their resistance against mould, stain, decay and moisture are lacking.

Wood and other organic materials are generally heterogeneous in terms of their anatomical and chemical constitution and their susceptibility to different decay and staining organisms, weathering, moisture and fire. The degradation agents themselves and the exposure conditions are also very variable, so it is no surprise that determining the performance of bio-based building materials is a major challenge, even without adding the variety of measures used to enhance the performances.

Performance studies are recognised as the starting point for the next step of research of bio-based materials and specifically performance modelling. This topic is described in Chapter 8 in detail. However, understanding of modelling is not possible without detailed understanding of the performance.

The concept of this chapter is to give an overview of the different performances, methods for their assessment and issues related to this phenomenon. It is somehow believed that this chapter will open more questions than provide the answers, hoping that this will inspire many new scientists to improve the knowledge of the performance of various bio-based materials.

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00005-7
© 2017 Elsevier Ltd. All rights reserved.

5.2 Function

C. Brischke[*,†], *M. Humar*[‡], *S. Thelandersson*[§]
*Leibniz University Hannover, Hannover, Germany
[†]University of Göttingen, Göttingen, Germany
[‡]University of Ljubljana, Ljubljana, Slovenia
[§]Lund University, Lund, Sweden

5.2.1 Bio-based materials for structural purposes

Generally, the requirements on a building material are very different depending on the function it shall have in the built facility. An important distinction is whether the material is used for structural or non-structural purposes.

The definition of structural purpose here means that the material is used in the main load-bearing structure. The primary requirement in this case is sufficient strength and stiffness. The leading general requirements on the load-bearing structure emanate from human safety; that is, the consequences of failure are usually serious. This means that the probability of failure must be strictly controlled and kept to a very low level. Concerning the structural material, the variability in strength and stiffness must be handled in a rational way, and control systems must be implemented in practice. This is usually a challenge for bio-based materials compared with manufactured materials such as steel and concrete, where systems to safeguard structural performance are well developed. In addition to the basic requirements of strength and stiffness on structural materials, durability covering the lifetime of a building must be ensured. It is often not feasible to replace the main structure in a built facility, even if secondary elements can be replaced at acceptable costs. For bio-based materials, durability or service life depends strongly on climatic exposure. Durability is further treated in Section 5.3. Another aspect is that the load-bearing structure shall be safe in the case of fire in the building. This is another challenge since most bio-based materials are combustible. This is further treated in Section 5.7. Furthermore, the material must be capable of providing joints between structural elements to transfer forces in the building systems. For buildings with main structures based on solid wood, glulam or cross-laminated timber (*CLT*), this is a crucial point for the competitiveness of the system. The anisotropic nature of the material implies that special solutions are needed for connections. In addition, it should be considered that the majority of structural performance studies have been performed on wood and glulam beams. Considerably, less information is available about other materials, and data from wood are not always transferable to other bio-based materials, even if both are lignocellulosic.

Recommendations for service life of load-bearing structures are given in EN 1990 (CEN (2012c)) Section 2.3. These are summarised in Table 5.1.

5.2.2 Bio-based materials for non-structural purposes

When bio-based materials are used for non-structural purposes, attributes other than strength become important. The function of a building component is strongly dependent on the intended use and defined by the user as illustrated in Fig. 5.1.

Table 5.1 Indicative design working life, according to Eurocode 5 (CEN, 2012c)

Design working life category	Indicative design working life (years)	Examples
1	10	Temporary structures
2	10–25	Replaceable structural parts
3	15–30	Agricultural and similar structures
4	50	Building structures or other common structures
5	100	Monumental building structures, bridges and other civil engineering structures

Fig. 5.1 Aesthetic performance. *Left*: Function of a riverside decking made from wood-polymer composites in Tartu, Estonia, defined by individuals. *Right*: Phone box in Kaunas, Lithuania. Function of providing shelter to humans still provided, although aesthetical appearance is poor.

Depending on the respective application, functionality based on aesthetics, dimensional and shape stability, stiffness and hardness, slip resistance, thermal insulation, acoustics and well-being, each of these will be duly considered herein.

5.2.2.1 Aesthetics

The aesthetic appearance of building components can be decisive for their serviceability. Even though a component can still fulfill other functions such as load-bearing capacity, protecting the building envelope from weathering or providing shelter, it might be replaced due to its optical appearance. The acceptance threshold is hereby clearly dependent on the human individual and depends on the respective application (e.g. Englund, 2013; Sandak and Negri, 2005; Brischke and Kaudewitz, 2015). More details about the aesthetic function of bio-based building materials are addressed in Section 5.5. Typical greying due to weathering is one of the most visible phenomena (Fig. 5.2).

5.2.2.2 Dimensional and shape stability

Lignocellulosic materials suffer usually from anisotropy and are subject of swelling and shrinking. Consequently, dimensional changes can also alter their shape. True-to-size components in the building sector made from bio-based materials

Fig. 5.2 Aesthetic appearance of bio-based building materials. *Left*: Old and new roof shingles from Kranjska Gora, Slovenia. *Right*: Setup for determining acceptance levels of users of wooden facades and decking (from Kaudewitz, 2016). *Below*, model house in Ljubljana. South façade in October 2013 *(left)* at the beginning of the test and October 2015 *(right)*.

Fig. 5.3 Dimensional stability of wooden building components. *Left*: Shingles damage due to the swelling of wood. Picture was taken in Ljubljana zoo. *Right*: Warping of black locust (*Robinia pseudoacacia* L.) boards of a decking at the entrance of a research institute in Bordeaux, France.

are mainly doors and windows (Fig. 5.3). Their key function is to open and close smoothly, which cannot be fulfilled if their dimension and shape changes significantly. Other products less sensitive to dimensional changes are shutters and garden doors or gates. Products that are mainly insensitive to dimensional changes are claddings, sound barriers, screens, or fence posts, provided they have been designed with sufficient scope for dimensional movement. As illustrated in Fig. 5.3, extreme deformation can also cause danger, for example, in terms of tripping hazards on a wooden deck.

5.2.2.3 Stiffness and hardness

Various mechanical surface properties become relevant if surfaces made from bio-based building materials are exposed to wear, abrasion and other mechanical dynamic impacts. In contrast to their strength properties and load-bearing capacity, the structural integrity and hardness of the material determine their ability to withstand impression on small areas, sanding, cutting, scratching and other types of wear. The wear effect of walking persons is often intensified by abrasive particles, for example, sand, dust, or winter grit (Fig. 5.4). The resistance against abrasion strongly depends on the material, and anatomic differences may become evident, for example, in the form of washboard effect, as a result of differences between early and late wood (Fig. 5.4).

5.2.2.4 Slip resistance

In moist conditions, predominately during winter, wooden surfaces can become slippery. This effect is even more prominent when the moist conditions combine with thin films of soft-rot fungi and bacteria formed on the surface. This phenomenon is known as a biofilm. Biofilms are usually slimy layers (films), where bacteria, algae, fungi or protozoans are colonising on the interface to solid building materials but not affecting the material

Fig. 5.4 Hardness and wear resistance of floorings. *Left*: Wear intensified by the use of severely abrasive grit during winter time on an Azobé (*Lophira alata* Banks) bridge flooring in Hannover, Germany. *Right*: Washboard effect observed on Scots pine sapwood (*Pinus sylvestris* L.) specimens after 3 years′ exposure at the beach of Portsmouth, United Kingdom.

Fig. 5.5 Slip resistance of wood-based floorings. *Left*: Degraded decks made of *WPC* in Annecy, France. *Right*: Wooden deck of a pedestrian timber bridge in Essing, Germany, made from notched Azobé boards covered with snow.

itself. This effect can be rather dangerous for pedestrians. In order to avoid this phenomenon, wood is frequently profiled to improve contact between foot and wood (Fig. 5.5). However, profiling increases relative surface and can act like water traps. Slip risk can also be avoided through incising techniques. Although incising is predominately used for improving the penetration in wood in the United States, this pretreatment reduces the slippery of the flooring. Additionally, it should be noted that slip risk is not only characteristic to wood but can appear on wood plastic composites, concrete, marble, etc.

5.2.2.5 Thermal insulation

Thermal performance of bio-based building materials predominately depends on two factors: long-term stability and the fact that the majority of insulation materials perform poorly if they get wet. Structural stability is predominately important for loose fibre insulation that is introduced into the compartments in the walls with air stream, as typified by loose fibre cellulose insulation. Typical density of such cellulose insulation is between 50 and 80 kg/m^3. Due to its loose fill introduction (Fig. 5.6, left) it is possible that within a service life of 50 years such fibre insulation can collapse and compact, leaving thermal bridges on the top. More challenging is the effect of

Fig. 5.6 Thermal performance. *Left*: Loose cellulose fibres injected into the compartments after removal of outside wall. *Right*: Sheep wool insulation.

moisture on bio-based insulation. The majority of insulations will collapse completely as soon as they become wet. Even if the insulations are dried again, their porous structure cannot be recovered. The best moisture performing bio-based insulation is sheep wool (Fig. 5.6, right) (Curling and Ormondroyd, 2016).

A comparison of the thermal properties of some bio-based insulation materials with those of other materials is given in Table 5.2.

Table 5.2 Basic thermal characteristics of the most important bio-based and conventional building materials

Material	ρ (kg/m^3)	c (J/kg K)	λ (W/m K)	μ (–)
Brick	1200	920	0.52	4
Concrete with stone aggregates	2500	960	2.33	90
Wood				
Oak	700	2090	0.21	40
Spruce and pine	500–600	2090	0.14	70
Extruded polystyrene (*EPS*)	60	1500	0.040	250
	20	1500	0.030	80
Sheep wool	20	900	0.040	1
Coconut fibres	100	1600	0.045	1
Low-density fibre boards	190	2000	0.045	10
Glass wool	80	840	0.038	1
	60	840	0.034	1
	30	840	0.034	1
	23	840	0.032	1
	14	840	0.032	1
Stone wool	180	840	0.039	1
	160	840	0.038	1
	100	840	0.037	1
	80	840	0.034	1
	30	840	0.033	1
Cellulose fibres	85	1800	0.040	1
Cotton	20	840	0.040	1
Glass foam	140	1100	0.060	4
Polyurethane	80	1500	0.040	100
foam	15	1500	0.025	30

Fig. 5.7 Acoustic performance. *Left*: Old railway ties used as sound barrier. *Right*: Sound absorbing panels.

5.2.2.6 Acoustic protection

Noise barriers are frequently made from wood and bamboo (Fig. 5.7). They are not necessarily required to look appealing. In contrast, often they are overgrown by plants, which can improve their potential to absorb traffic sound, and as a result, their visibility is diminished. The acoustic effectiveness of sound barriers can be measured in terms of insertion loss and transmission loss. Insertion loss is the noise reduction that a barrier causes if it is built between the source and receiver. Transmission loss is a measure of how much sound travels through a barrier. Together, these two measures give the designer a sense of the acoustic effectiveness of a proposed barrier. Insertion loss is a measurement that includes the diffraction of sound waves over the top of a sound barrier. Because most barriers block sound transmission, most sound that reaches receivers behind the barrier diffracts over the top of the barrier. The importance of sound waves diffracting over the top of the barriers is reinforced by research on the special treatment of barrier tops (Boothby *et al.*, 2001).

The acoustic properties of bio-based building materials itself play an important role within buildings, whereby ambience and impact sound need to be considered separately. These materials are used at the buildings with low environmental impact. One of the frequent drawbacks of the bio-based materials is higher price compared with the conventional materials. This topic is described in detail in the report of Boothby and coworkers (2001). Fig. 5.7 shows different sound absorbing panels made from wood-based products such as particle boards.

5.2.2.7 Well-being

The thermal properties of building materials play an important role for human well-being. With direct skin contact between people and building components, for example, flooring materials, the ability of these components to release or draw heat needs to be considered. Floors may feel differently warm or cold, although their temperature is the same (Waltjen, 2003). The individual thermal sensation is determined by the contact temperature, which is reached immediately after the sole of the foot was put on the floor. The contact temperature depends not only on the surface temperature of the floor but also on the thermal conductivity, the density and the thermal capacity of the flooring

Fig. 5.8 Human well-being when living with bio-based building materials. *Left*: Spa (Sečovlje, Slovenia) with decking made of larch *(Larix decidua)* wood that enables comfort when walking barefoot. *Right*: Interior of the bathroom made of larch wood in Cortina d′Ampezzo, Italy.

material. Comparative measurements of critical heat flux densities on various building and flooring materials by Brischke *et al.* (2011) showed that wood and other organic materials increase the thermal comfort if direct contact with human skin is requested or unavoidable, and it is therefore recommended for outdoor applications such as terrace floorings, swimming pool borders (Fig. 5.8), decking or beach and garden pathways.

Various studies showed that wood used inside of buildings have a positive effect of human overall well-being. Most remarkably, Grote (2012) showed that sleeping in beds made from Stone pine (*Pinus cembra*) made humans hearts beating slower. Additionally, it was indicated that pupils that are studying in classrooms with a wooden interior are more calm and are feeling better than pupils in classical classrooms. It was presumed that this is an influence of the wood texture and easily volatile compounds (Pohleven, 2015).

5.3 Durability

J. Van Acker[*], *S. Palanti*[†]
*Ghent University (UGent), Ghent, Belgium
†CNR IVALSA, Trees and Timber Institute, Sesto Fiorentino, Italy

5.3.1 Introduction

According to the European standard EN 1001-2 (CEN (2005c)), the definition of the principle of classification is given as follows: durability is the resistance of wood to destruction by wood-destroying organisms. The durability of a wood species to various

Table 5.3 Life expectancy of 2 × 2 inch stakes in ground contact (Findlay, 1985)

Durability class	Life of test stake in the field, temperate, England	Life of test stake in the field, tropics, Fiji	Average loss in dry weight (%)
D1: very durable	Over 25 years	Over 10 years	Nil or negligible
D2: durable	15–20 years	5–10 years	Up to 5%
D3: moderately durable	10–15 years	(Not given)	5%–10%
D4: non-durable	5–10 years	2–5 years	10%–30%
D5: perishable	Less than 5 years	Less than 2 years	Over 30%

wood-destroying organisms is tested using methods based on relevant European standards. The range of variation of properties within a species is taken into account by the use of replicate specimens. Results are compared with those of a reference species. Based on test results, the natural durability of the wood species to the various agents of biological attack is classified within a five-grade scale for fungal attack, a two-grade scale for dry wood-destroying beetles and a three-grade scale for termites and marine organisms. The natural durability of wood species has always been linked to service life or life expectancy, however solely based in ground contact conditions.

Findlay (1985) summarised it is usual to classify timber into five classes with respect to their durability. In his table reproduced below, the corresponding 'life' of a 2 × 2 inch stake, in average soil, is compared with the average loss in dry weight percent suffered in laboratory tests (Table 5.3).

Several lists on natural durability have been published over the last decades, for example, Scheffer and Morrell (1998), the Australian standard AS 5604 (AS, 2005) and the European standard EN 350-2 (CEN (1994b)), and an overview of tropical species is presented very well in the web-tool Tropix of CIRAD (Paradis *et al.*, 2011).

5.3.2 Biological decay and natural durability

Durability in a traditional approach can be defined as the resistance of wood and wood-based products against biological organisms and can be considered inherent or achieved with the help of wood protection processes. This so-called natural or intrinsic durability is considered key when selecting a wood product for a specific application. It has a considerable impact on the service life performance. Both natural or intrinsic durability and enhanced resistance should be combined with external parameters such as design, maintenance and exposure level to obtain a modern performance-based approach of wooden components or commodities.

Whilst there is a natural durability or intrinsic resistance of a wood species, resultant attack by an organism is usually referred to as fungal decay. Further to fungal decay, it is also known that insects can decay and destroy wood being used for construction purposes. Fungi can decay sapwood and heartwood, and the durability class is always referred to the durability of heartwood, because most of

the fungi decay fully the sapwood. Insects, with some exceptions (e.g. termites), decay merely the sapwood and can use the heartwood for emerging exit holes.

Focusing on biological decay, it can be stated that wood used in constructions can be degraded in a similar way as wood in the forest ecosystem. Basically, wooden commodities suffer from wood-destroying fungi and insects.

Carey (1975) described that identification of the type of fungi present may be gleaned from a sample:

- Moulds are mainly evident as surface growths, which are often powdery when sporing. The wood itself may not be discoloured in depth.
- Sapstain or blue stain may be accompanied by very dark surface growths. The chief characteristic is pronounced as darkening of sapwoods in shades of blue to grey-black, often as radial streaks when viewed on cross-cut surfaces. Less frequently, other colourations may occur. Sapstain is a certain indication of the presence of sapwood. Neither sapstain fungi nor moulds cause evident weakening of the wood.
- Soft rot produces a superficial softening of timber exposed under water, often leading to erosion of the surface. In other circumstances, softening may penetrate more deeply from the surfaces. Attacked wood may be darkened and cross-cracked when dry though sometimes the only evidence of attack is a softening detectable by prodding or by the short fracture of the wood when splinters are levered out with the point of a knife. Soft-rot fungi are not Basidiomycetes as the hereafter-mentioned wood-rotting fungi but are *Ascomycetes* and fungi imperfecti.
- Basidiomycetes produce decay in various forms; the incipient stage of any particular rot is often very different in appearance from the more advanced stages. Two main types can be distinguished: brown rots and white rots.
- Brown rots induce wood eventually to become dark brown, and the final stages tend to break up into brick-shaped pieces as a result of cracking both along and across the grain. Severely attacked wood can readily be crumbled with the fingers. Chemically, brown rots attack only the cellulose and associated carbohydrates, leaving the lignin practically unchanged. The pattern after the attack with checks perpendicular and parallel to the fibre direction is called destruction but sometimes also denominated as cuboidal rot.
- White rots may initially darken the wood, but eventually, they bleach it to a very much lighter colour. The decay may be general or may occur in distinct ‘pockets’. Even in an advanced stage, white-rotted wood does not powder under pressure, although it may disintegrate into a lint-like material (fibrous rot). Chemically, white rots can attack both the cellulose and the lignin components of the wood.

The three primary decay types (white rot, brown rot and soft rot) disguise considerable variations in detail of the patterns and dynamics of the process of interaction with and degradation of woody cell walls (Rayner and Boddy, 1988; Nilsson, 1985). A spectrum of decay types is being observed since decay produced by certain non-hymenomycetous fungi (Ascomycotina and Heterobasidiomycetes) are studied more intensively.

Even with respect to decay caused by *Hymenomycetes*, at least two distinct classes of white rot occur. On the one hand, the lignin and polysaccharide components are broken down simultaneously (‘simultaneous rot’), while on the other hand, a wide variety of *Basidiomycotina* have now clearly been shown to remove lignin selectively (‘selective delignification’), prior to the polysaccharide components.

Brown rots may involve a non-enzymic mechanism of lignocellulose breakdown correlating with the fact that the majority of fungi causing this decay have been found not to be able to degrade crystalline cellulose in pure culture. However, a second group of brown-rot fungi occur in the *Coniophoraceae*, which is capable of degrading acid-swollen cellulose.

Also, non-basidiomycete fungi may be capable of brown-rot-like patterns of attack on lignocellulose.

Unlike brown rots and some white rots, a distinguishing feature of soft rots is that woody cell wall breakdown invariably occurs in the immediate vicinity of hyphae. Furthermore, lignin removal is absent or slow and partial. The localised degradation of the woody cell walls can occur either within the S2 layer ('type 1' soft rot), producing cavities, or adjacent to the lumen ('type 2' soft rot), giving rise to erosion grooves. Different species of soft-rot fungi may be capable of producing only type 1 attack, only type 2 attack or both (Nilsson, 1976). Type 2 attack is infrequent in softwoods, which may be due to increased resistance to degradation of the S3 layer. Also, bacteria are reported being responsible for the part of the decay features observed (Nilsson and Holt, 1983).

Wood used for construction purposes is primarily endangered by basidiomycetes fungi. In ground contact and under specific conditions like cooling towers, soft-rot fungi are additionally present. Blue stain fungi, moulds and sapstain are merely only of aesthetic importance.

The durability against insects depends on different factors such as wood species (among Cerambycidae, some species are specialised only for hardwood and others for softwood), anatomical characteristics (e.g. tyloses, aspirated and encrusted pits), extractive contents (*Lyctus* spp. can attack hardwood with huge vessels and high amount of starch) and mineral inclusions (some tropical species are resistant to termites that have high contents of silica). Further, insects can attack also dry wood, and this factor represents a hazard for indoor situations. Another important factor is the age of the wood (time since primary processing) since we can distinguish what kind of dry-wood insect, such as Anobids and termites that can decay also old wood, contrary to Cerambycidae such as *Hylotrupes bajulus* (the wide spread house longhorn beetle), which can only attack recent wood probably because the species does not have symbionts (Palanti *et al.*, 2010).

Wood products in use throughout the world are also subject to infestation by a wide variety of termites and beetles and by a few species of ants and bees. Termites cause by far the greatest economic loss but are mostly restricted to subtropical and tropical regions. Nevertheless, in Southern European countries like Spain, Portugal, Greece, Italy and France, endemic infestation of termites occurs, and for this reason, some precautions are adopted such as national laws, preservative treatments and monitoring.

Five groups of wood-destroying beetles can be identified:

- Furniture beetles (Anobiidae) attacking old hardwood and softwood
- True powder-post beetles (Lyctidae) on new starch containing hardwood
- False powder-post beetles (Bostrychidae) present in similar ecological niche as Lyctidae
- Long-horned borers (Cerambycidae) a major risk for softwoods
- Weevils (Curculinoidae) on both old hardwood and softwood but with lower level of risk

The most destructive beetle pests are those which attack seasoned wood in service, for example, *Anobium punctatum*, *H. bajulus* and *Lyctus brunneus*.

In sea water, wood may also suffer from marine borers primarily shipworms, that is, *Teredo* spp., molluscs that grow as they tunnel the wood creating an extensive honeycombed structure, and gribble, that is, *Limnoria* spp., small crustaceans, which attack the surface of wood.

Most of the European wood species are non-durable to marine organisms, and the only solutions to limit the importation of durable tropical species are the preservative treatments of European treatable species, some non-biocidal strategies (modified wood) and physical barriers.

5.3.3 Use classes and enhancing durability

Fungi require adequate moisture to provide a medium for the outward diffusion of the extracellular enzymes and other breakdown systems produced and for the transport of mineral nutrients and degradations products in the opposite direction. The optimal condition for decay by the most active white- and brown-rot fungi is above the fibre saturation point. With soft-rot decay, higher moisture contents are generally optimal, but additional water leads to suffocating of the basidiomycete fungi due to lack of aeration. A temperature of 25–30°C is optimal for the growth of most fungi. Below 12°C, decay is usually very slow and few wood-destroying fungi are active above 40°C.

In order to categorise the different end-use commodities according to their potential biological hazard mostly related to fungal decay, hazard classes and later use classes have been specified in the European standard EN 335 (CEN (2013a)). The purpose of standardisation of hazard/use classes is mainly related to organise wood preservation technology and homologation of preservatives in a more homogeneous way throughout Europe. For the assessment of the efficacy of wood preservatives, requirements are formulated in EN 599-1 (CEN (2009a)) for each of the biological hazard classes. The requirements cover the method of application of the preservative (superficial application or penetrating treatment) and the particular resistance of the treated wood to which the preservative intends to be applied (softwoods or hardwoods). The EN 599-1 (CEN (2009a)) requires a range of tests to be carried out using the formulated product. The results of all these tests allow the critical value, representing the minimum amount of product required to provide complete protection of the reference wood species used in the laboratory biological test, to be calculated for each use class considered. The critical values must then be translated into quantities of product to be industrially applied into the structural timber zone to be protected. These minimum retention levels can be achieved with specific wood preservation processes, taking into account the product penetration characteristics, the industrial treatment technique used, the intended purposes and the particular characteristics and sizes of the timber. All these elements are considered by national regulatory bodies, and these rules are applied when evaluating products for homologation.

The service life concept has become increasingly important in Europe both related to the interaction between or comparison of the performance of different competitive building materials and integrating performance assessment of different wood products.

The performance or service life of wood products is based on the different interactions between end use and specific interacting or degrading parameters. The end use can be translated as wood products with a specific design under a macroclimate-microclimate impact. This interaction results in an exposure dosage. This exposure (dosage) can be identified as the degree of exposure being a potential indicator for decay. The parameter design or usage can be linked to use classes (*UCs*) 1–5 as defined in EN 335 (CEN (2013a)). Next to the geographically defined macroclimate impact, the microclimate is predominantly important for UCs 2 and 3 and less or even not relevant for interior dry (UC1) and in soil and (sea) water contact (UC4/5) usage. The design of the wooden commodities and structures plays an important role in the service life; for example, the service life of wood increases when avoiding ground contact, covering the end grain, avoiding the moisture traps, *etc*. This topic is more precisely described in Chapters 4.6 and 5.4, respectively.

Each wood product in use has a material resistance against degrading factors. For each biological agent of concern – related to degradation of wood and hence having an impact on the service life – a specific combination of the inherent durability (presence of toxic components) and moisture dynamics (wetting and drying properties resulting in time of wetness, *ToW*) will characterise the wood product with a specific level of material resistance. The (material) resistance of a wood product is in fact the degree of resistance related to a biological hazard. Different biological (decaying) agents can be linked to hazard classes 1–5, which were commonly used prior to the definition of use classes in EN 335 (CEN (2013a)) and ISO 21887 (ISO (2007)). The inherent durability can be natural durability as defined in EN 350 (CEN (1994a,b)) or enhanced durability through wood preservation as steered by EN 599-1 (CEN (2013b)). This inherent durability parameter has recently been complemented with an indicator on moisture dynamics, which inevitably is less or even not relevant when discussing dry-wood insects (UC1) or soft rot/termites/marine organisms (UC4/5).

The service life (prediction) framework requires multi-objective optimisation, taking into account many interacting parameters. To ensure that this fits reality or service life expectations, it is important to identify relevant reference materials and products. These should be functional for both inherent durability and moisture dynamics and linked to specific biological agents.

5.3.4 Integrated approach of durability

Over the last few decades, approaches dealing with natural durability and wood preservation have come closer to each other. Some elements are considered contributing to a more integrated concept.

Testing methods have been developed specifically for assessing natural durability CEN/TS, 15083-1 and CEN/TS, 15083-2 (CEN, 2005a,b)) alongside the test methods specific for assessing the performance of wood preservatives (EN 113, CEN, 1996; ENV 807, ENV, 2001). Harmonisation of these standards will allow for a more integrated approach.

Many modified materials are assessed by either or both natural durability and biocidal efficacy approaches, for example, thermally modified timber (*TMT*) classified according to EN 350 (CEN (1994a,b)).

Service life prediction (*SLP*) is evolving from the definition when wood preservation can be considered required or useful to a methodology to integrate the performance prediction of the commodities based on the intrinsic durability, the moisture dynamics and the local specific microclimate. The project 'Performance standards for wood in construction – delivering customer service life needs (PerformWood)' – has been the basis to activate the revision of EN 460 (CEN (1994c)): 'Natural durability of solid wood – Guide to the durability requirements for wood to be used in use classes'.

In EN 350-2 (CEN (1994b)), wood species are listed with information on their durability, and recently, it has been decided to include this as an informative annex to the EN 350 integrated document.

Durability of wood and non-wood products is looking for options to assess the performance of wood species, wood products, preservative-treated wood, modified wood and non-wood lignocellulosic-based materials in a similar way. For preservative-treated wood, this means complementing the approach of biocidal efficacy testing, especially when focusing on surface treatments using an additional method to EN 113 (CEN (1996)) for envelope performance assessment (EN 839, CEN, 2014d). For intrinsic or enhanced durability commodities, the use of preconditioning methods like EN 73 (CEN (2014c)) and EN 84 (CEN (1997)) is also becoming more critical depending on the use classes envisaged.

Van Acker *et al.* (2014a–c) combined and integrated durability of wood species, engineered wood products (*EWP*), modified wood and treated wood in a service life concept. In Section 5.3.5, this is used as a basis to discuss durability in relation to use classes.

5.3.5 Durability and service life concept for wood products

Typically, wood or timber species have been classified for natural durability using a service life approach by means of graveyard type of field testing. High variability is a concern, and predicting service life for applications out of ground contact leads often to substantial debate (Kutnik, 2013; Suttie *et al.*, 2013). To ensure minimum requirements are met, often highly durable species, mainly tropical hardwoods, are selected, whilst adequate performance is feasible with less durable species. This is in part leading to selective harvesting and limits sustainable management of tropical forests. Focusing on softwoods, it can be stated that the intrinsic or inherent durability is often insufficient, and different methods with increasing impact are used to enhance the material resistance when the products are intended to be used under harsher circumstances.

Especially heavy-duty applications like transmission poles and railway sleepers have triggered wood preservation. In many countries, wood preservation is still considered mainly for use class 4 applications. The assessment of toxic threshold levels for the used biocides is still defined accordingly. Field testing in ground contact combined with a so-called 'no risk' approach is the basis to continue using heavy-duty preservatives like creosote, copper chromium arsenic (*CCA*) and pentachlorophenol (*PCP*). However, wood preservation evolved and exterior out of ground applications have become more apparent. When soft rot is of no concern, the assessment of wood

preservatives in ground contact may lead to excessive requirements for biocides or overkill of recommended or required retentions. Furthermore, in ground contact (or water contact), a continuous supply of water guarantees the development of fungi. Above ground, the climatic conditions are far more dominant and can allow to ensure longer service life by means of protection by design and are also impacted by coatings. Dealing with the interior climate, for example, use class 1, the risk of getting higher moisture content in wood for a longer period depends not only on the interior climate. Moisture is linked to dampness and is increased when condensation and/or leakages are involved. A critical parameter here is to lower the risk of increased moisture content. In practice, wood preservation is linked to industry involved in producing, formulating and applying biocides and hence often related to other application areas of such active components.

Over the last decades, additional actors have been coming to the field of enhanced durability. Technologies working under the denominator wood modification claim to enable this without using biocides. The product brand names often are referred to as 'new' wood species, and the main focus might well be on increasing other properties like dimensional stability or weathering performance. Besides TMT, several chemical modification systems are present especially on the European market, for example, acetylation and furfurylation. The so-called non-biocidal systems also include several methodologies to lower the impact of moisture and are known as oil treatments and hydrophobation like the use of organosilicon compounds. Clearly, these methods come close to the role of exterior wood coatings. Currently, the industry involved in these technologies seems to be hardly linked to the producers of wood preservatives. These technologies are presented in detail in Chapter 4.

On the scene of service life of wood products, not only different treatments to enhance durability are of importance. Since the middle of the last century, a lot of innovative wood products have been developed, all having an impact on the moisture dynamics and hence on the rate of fungal degradation or service life. For construction end uses, commodities have been developed, often intended for protected interior use. Especially under use class 2, the processing of wood into different EWP lowers the risk of high humidity over longer periods. Products like glued laminated timber (glulam), cross laminated timber (CLT), laminated veneer lumber (*LVL*), laminated strand lumber (*LSL*), parallel strand lumber (*PSL*) and other structural composite lumber all have different moisture dynamics to solid timber. Furthermore, I-joists and wood I-beams combine several of these and link with the wood-based panels (*WBP*) like plywood and oriented strand board (*OSB*). Both are also considered for exterior applications, and again a major impact of coatings should be considered. Coated plywood is an eminent product in this respect. In the group of innovative wood products, one should not forget several composite products being developed next to the more traditional wood composites. With focus on decking and cladding, wood polymer/plastic composites (WPC) are clearly stating argumentation of moisture control as one of the main features (Defoirdt *et al.*, 2009). Similarly, natural fibre composites (*NFC*) based on other 'non-wood' lignocellulosics have similar issues on moisture control to ensure service life in exterior applications. Unfortunately, often the industry involved in all these products has limited links to the companies involved in wood preservation and wood modification.

The methodology to assess service life performance of wood products is becoming very relevant since the concept has been developed into the standard ISO 15686-8 (ISO (2008)). This eighth part is focusing on service life planning across different construction materials.

5.3.5.1 *In ground contact conditions*

The durability of wood species has traditionally been assessed related to the service life in ground contact. The traditional methodology to assess the durability of wood species has been based on the service life observed from stakes, both based on general experience and intentionally tested.

Wood species and later also some derived wood products have been classified in durability classes according to their performance in ground contact. Several lists have been developed differently, depending on test sites (climatic region), classification methodology and limit state values used.

Specific for in-ground conditions is the presence of moisture in a semi-continuous high level. Hence, wood species cannot resist decay by means of controlling moisture dynamics. Furthermore, the presence of specific additional decaying soft-rot organisms and in many regions also termites challenges the material resistance to the maximum. Further, living trees develops protective measures, during heartwood formation through the deposition of chemical components (extractives) to overcome decay whilst a living organism.

5.3.5.2 *Exterior out of ground contact conditions*

The durability of wood species has traditionally been assessed related to service class 4, in ground contact. Augusta and Rapp (2003) showed that natural durability when focusing on use class 3 can considerably alter the classification of wood species. Especially for use class 3, more specific innovation and development efforts have been the basis for new strategies related to the durability of wood and the concept of service life. In this paragraph, an overview is presented on how this can be handled.

An integrated approach related to service life prediction for natural durability, wood preservation, wood modification and innovative wood products is a major challenge for the wood sector. The framework for SLP of wood and wood products is based on the interaction of an exposure dosage and a material resistance.

The exposure dosage is a measure for the degree of exposure indicating the potential of decay. As presented in Fig. 5.9, the macroclimate as defined by the geographical location and climate data for the region together with local impact identified as microclimate will lead to specific ToW of the wooden product (Rapp *et al.*, 2000; Brischke and Rapp, 2010). Design will act as an additional parameter lowering or sometimes increasing (e.g. water trapping) the impact of the climate factors. Clearly, the climate and especially the microclimate is not or less relevant when considering applications 'interior dry' (UC1) and 'in soil and (sea) water contact' (UC4/5).

Any wood species and wood product – treated or not – will have a material resistance against biological agents. Material resistance can be used as a parameter to express the degree of resistance related to a biological hazard (Fig. 5.10). The biological agents of concern differ depending on the use classes and even more to the earlier definition

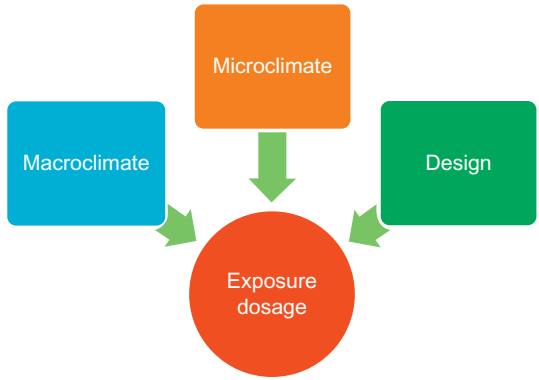


Fig. 5.9 Exposure dosage is a combined parameter including macro- and microclimate and design components.

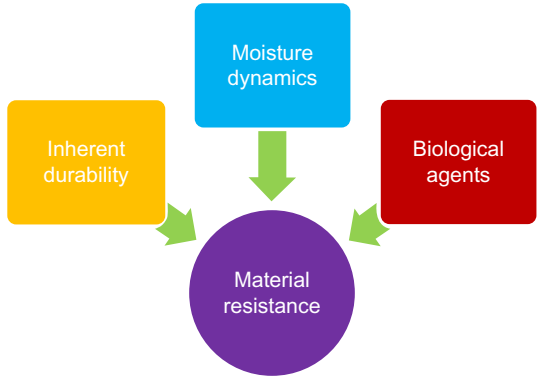


Fig. 5.10 Material resistance of wood products is a combination of inherent durability (toxicity) and moisture dynamics, and these are relevant for the different biological agents.

of biological hazard classes. When focusing on fungal decay, the inherent durability can be linked to the presence of biocidal components and hence the level of toxicity towards the fungi of concern. Additionally, it is relevant that the substrate contains a sufficient level of moisture over time. The resistance of any substrate to get wet and the ease or difficulty to dry fast when the wetting stopped can be expressed under the term moisture dynamics (Van den Bulcke *et al.*, 2013; Brischke *et al.*, 2014a,b; Van Acker *et al.*, 2014a–c). This parameter is inevitably less relevant when discussing biological agents like drywood insects (UC1) and soft rot/termites/sea organisms (UC4/5). In fact, the moisture content of wood is determinant in the diffusion of biological decay, but for the drywood insects and termites, the main factor is the local hazard. Some drywood insects such as anobids, cerambycid, *H. bajulus* and *Lyctus* spp are spread across all Europe; other species are dispersed only in specific areas (termites, *T. holosericeus* and other local species).

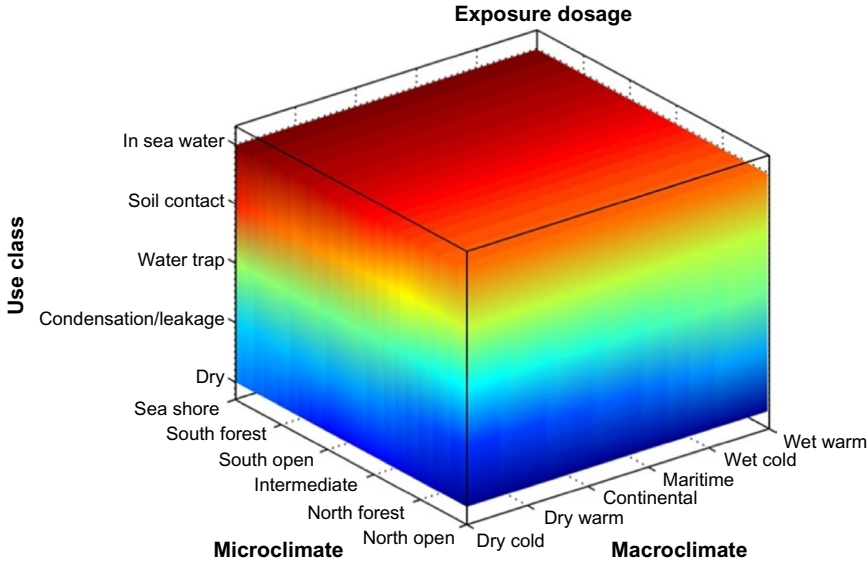


Fig. 5.11 Quasi-continuous outline of the exposure dosage (c.f. use classes) in relation to macroclimate, microclimate and design.

The parameter interaction defining exposure dosage as presented in Fig. 5.9 can be presented using three axes in a 3-D plot for each of them. In Fig. 5.11, the macroclimate is simply presented as ranging from dry cold to wet warm passing dry warm, continental, maritime and wet cold as intermediate levels. Although this presentation might assume some linear scale, the presentation is just to show what components could be considered. Any climate model that can depict the impact on the ToW could be used here; a well-known example is the Scheffer index (Scheffer, 1971). When the microclimatic impact is also added, some components are listed, and the increased impact is not always fully assured. Exposure to the south or north, whether forest cover is present or the exposure is fully open, and probably a full sea shore exposure will all have impact mainly on the drying component and limit or increase the ToW considerably. Finally, design qualification will also help in identifying different use class levels: (interior) dry, presence of condensation/leakage, out-of-ground contact water trap and finally contact with soils/water and even sea water. Fig. 5.11 uses a quasi-continuous approach with outcome levels 0 (blue) to 5 (red) linked to the harshness of the exposure or simply exposure dosage. The levels 2–3 will probably be most impacted by all variables and need careful concern on how to measure. The different exposure scenarios developed for field testing can be used to verify the parameter ToW. Recent work has developed a tool called continuous moisture measurements (*CMM*, Van den Bulcke *et al.*, 2009). Testing at field level also implies search for non-destructive testing methodology to identify test specimen degradation towards failure. A common approach is actually to work with simulation exposure using semi-field testing. This hybrid in-service testing also requires adequate statistical approaches, and hence, it is important to relate to probability density functions (*pdf*) of failure (Van den Bulcke *et al.*, 2013). When

using this approach for a construction commodity, failure can be assessed based on the detection/occurrence and impact of the decay/degradation but can also be registered based on ToW (Van den Bulcke *et al.*, 2014; Van Acker *et al.*, 2014a–c).

In contrast to exposure dosage, which is basically independent of the wood product, one should assess each commodity intended to perform for a certain time period (service life prediction, SLP). The material resistance is a set of characteristics that determines to what extent one can expect the material to withstand specific biological degradation or even all types of degradation (e.g. weathering). Fig. 5.12 represents as a quasi-continuous 3-D plot of the parameters' inherent durability, merely due to the presence of active biocidal ingredients, and moisture dynamics in combination with different biological hazards. The material resistance can be checked solely using laboratory testing. Since different biological agents are acting differently, it is necessary to have a multi-agent assessment installed considering that different combinations will be relevant depending on the maximum exposure dosage focused on. As indicated earlier, when dealing with fungal decay, it is relevant to assess *via* organism-related testing the 'nutritional value' or intrinsic nutritional quality/toxicity. Here, again, it is important to assess variability and reliability using, for example, life distributions (De Windt *et al.*, 2013). Next to that, there is a need to work on better methodology to assess the moisture dynamics, for example, by means of the material parameter moisture behaviour assessment by using a combination of dipping (absorption of liquid water) and drying (water vapour release) (Van Acker *et al.*, 2014a–c). Clearly, material using only aspects of moisture control will have some limitations but should anyhow be taken into account when considering increased service life. Here is also an option to link with the performance of coatings.

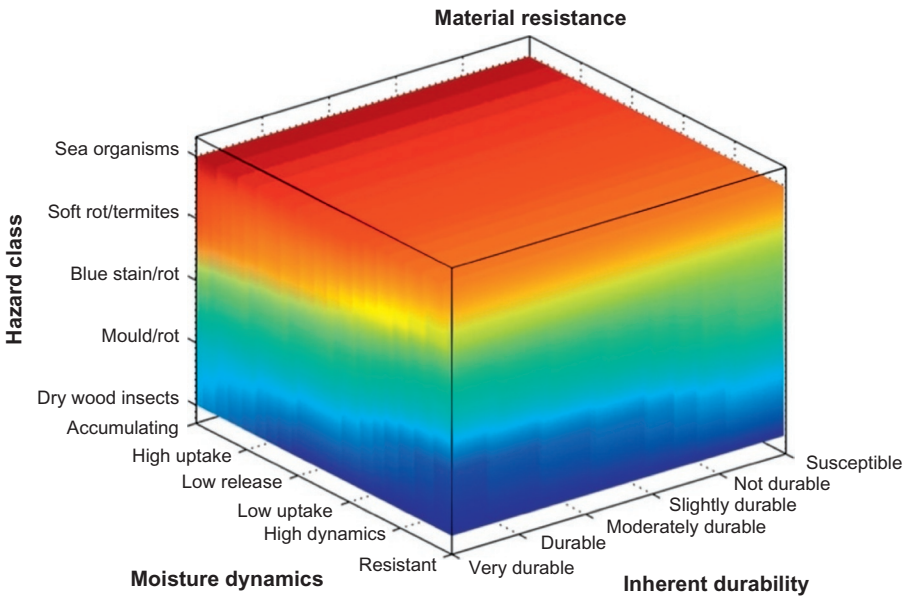


Fig. 5.12 Quasi-continuous outline of the material resistance in relation to inherent durability and moisture dynamics and interacting with biological agents (hazard approach).

Linking the in-service assessment of exposure dosage and the lab testing-based assessment of material resistance allows the combination of both integration and interaction. Integration is mainly linked to the fact that any exposure is somewhere located in the 3-D plot as presented in Fig. 5.11 and that any wooden commodity will have an intrinsic or enhanced material resistance that can be positioned on the 3-D plot in Fig. 5.12. The interaction, however, is based on what level of material resistance is required for a specific exposure dosage. This many-to-many link requires a (quasi-) discrete approach. For the exposure, a dosage range could be determined. Hence, a probability or priority of risk could be selected, for example, the most probable or number one (priority) biological agent. Based on selected laboratory testing, one could prioritise results and/or use weighing schemes. Adding input on reliability-based durability for each agent, the data on material resistance from lab testing should be used to predict in-service field data. Any qualification of performance of a wood product could use such an early predictor method but will still need to be followed up using full field exposure and assessment of end-use performance.

The concept of SLP is of major importance for the utilisation of wood and wood products. Many products are compared with alternatives based on man-made materials. Besides the ability to predict performance, it is also relevant to know what is actually expected from a specific commodity. In the EU project PerformWood (FP7 grant 19132 – www.performwood.eu) entitled 'Performance standards for wood in construction – delivering customer service life needs', several methods were used to gain better insight into this component. In Fig. 5.13, an outcome is presented based on the consultation of national experts. Clearly, the expected service life for cladding is lower in the warmer (southern) and more maritime (western) climate of Europe.

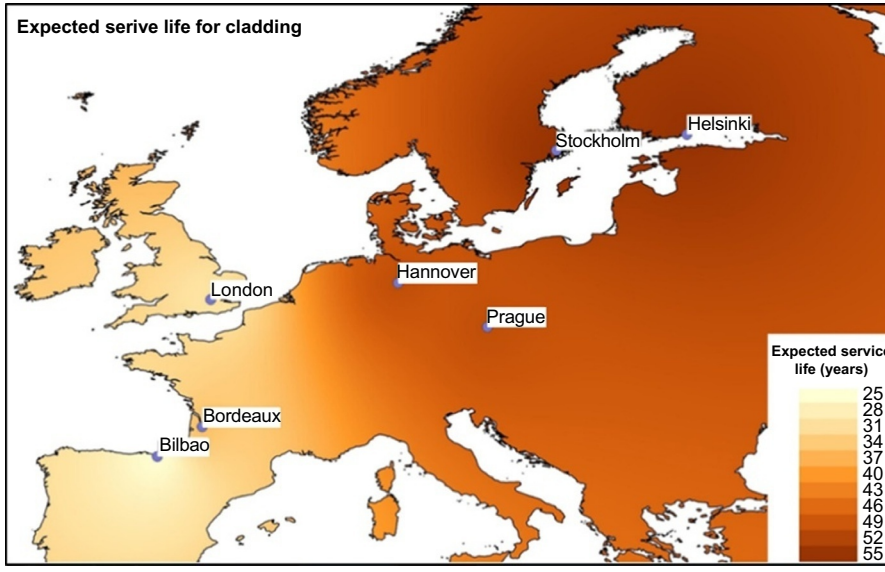


Fig. 5.13 Levels of expected service life (years) as provided through an expert survey within the EU project PerformWood.

People seem to expect a longer service life when they are used to a specific level of performance of the known materials used for a certain commodity.

The process of integration and interaction has created also some momentum related to standardisation. The project PerformWood provided a roadmap that was included in the new business plan of CEN TC 38 'wood durability' (Kutnik, 2013; Suttie *et al.*, 2013). A new working group, WG 28 'performance classification', was established dealing specifically with this topic. The main focus of this group is on integrating EN 599 (CEN, 2013b), dealing with wood preservation, and EN 350 (CEN (1994a,b)), dealing with wood durability, under a new EN 460 (CEN (1994c)) based on performance classes. A test protocol related to moisture dynamics was already presented, but harmonisation of fungal testing is also required to bring together test methodology to underpin the efficacy of biocides and the durability assessment of wood products.

5.3.5.3 Interior conditions

The durability of wood species becomes less relevant when we use the material indoors. Many wood components both non-structural and structural can last a long time when kept dry.

Resistance to insect degradation can be critical, and for some applications and regions, this is very relevant. This is considered key for use class 1 and hence mainly depending on whether the wooden objects are of high value and/or difficult to replace.

For some time, there has been a tendency to avoid durability requirements for some applications, for example, the existence of a use class 0 in the German standard DIN 68800-1 (DIN (2011)).

New products like CLT are in this respect discussed since maintenance and monitoring could be insufficient for long-term performance of these structural building components. These considerations become more important in certain regions like the Southern European countries where the hazard for biological decay, in terms of exposure dosage, is really high. The use class 2 and 1 environments are closely linked to building physics, and often the use class definitions, which are based on the potential biological decay risk or hazard, are linked to service classes as defined in EN 1995-1-1 (CEN (2004a,b)). The EN 1995-1-1 defines three service classes that are relevant to a designer when assessing strength values and calculating deformations for timber elements to be used in a construction. The service class 1 is corresponding to the climatic conditions leading up to 12% moisture content in softwood (60% *RH* and 20°C). With service class 2 being limited to 85% RH and wood moisture content of max 20%, one could see some similarity with the use class 1 according to EN 335 (CEN (2013a)). The service class 3 is referring to conditions that are more humid.

The approach or definition of service classes is also used related to bonding classes; for example, EN 314-2 (CEN (1993)) defines three classes of bond quality in relation to moisture defined conditions: dry, humid and exterior. Often, all these definitions are erroneously interchanged using the same value as basis for comparison. Often, CLT structures are exposed to use class 2–3 especially during construction phase or eventually during service life when connected to external walls or close to wet units, for example,

bathroom and kitchen. For this reason, a continuous monitoring is required to inform in advance the architect/engineer and afterwards the homeowner on the potential hazard.

5.3.5.4 Durability of wood products and non-wood materials

The presence of glue in wood products has been accepted as playing a role in the service life of WBP. For plywood, in particular, a lot of comparative testing has shown an impact of glue on some fungi especially just after production, but in general, it can be accepted that the intrinsic durability is very close to that of the wood species used. However, for these wood products, the moisture dynamics are considered very important and allow for considerable increase in service life when focusing on use class 2 and especially use class 3 (Van den Bulcke *et al.*, 2011; Li *et al.*, 2016). For assessing the durability of WBP, a specific methodology according to ENV 12038 (ENV (2002)) has been developed taking into account the panel shape and presence of glue. Testing of the durability of plywood according to standard procedures is sometimes not objective, predominantly as selection of the fungi can considerably influence the result (De Smet and Van Acker, 2006).

Although the impact of glue valid for plywood can be different for other WBP and EWP, it is significantly different for WPC. In these products, the wood part is sometimes less than 50%, and hence, moisture dynamics become a major driver in performance. Testing these products and NFC requires a critical wetting prior to testing (Defoirdt *et al.*, 2009).

The durability of non-wood products has been considered on several occasions and mostly linked to test methodologies developed for wood products. Examples of materials derived from monocots like palm trees and bamboo show the absence of heartwood components, as would be present with durable wood species. Enhanced performance linked to differences in moisture dynamics and density can however lead to an impact on service life (Jourez *et al.*, 2012; Wei *et al.*, 2013).

Bamboo is used around the world for construction purposes, especially in the tropics, but now, its utilisation is spreading in Europe. For this reason, a classification of its durability against decaying organisms is necessary. Termite resistance of different Hawaiian bamboo species was tested according to a 'no-choice test' (Hapukotuwa and Grace, 2011), and different susceptibility to termite attacks was found. Five bamboo species showed various resistances against white- and soft-rot fungi (Wei *et al.*, 2013).

Most non-wood bio-based materials are used in construction as insulation materials: Curling and co-authors (2015) applied wood durability test methods to non-wood materials (mineral wool, sheep's wool, wood fibres, cellulose flakes, etc.) and compared the results to those of Scots pine and beech. The outcome of this paper showed that only lignocellulosic materials were decayed, and that in some cases, the methods were not suitable.

Bio-based non-lignocellulosic materials such as sheep wool are biodegradable, and thus organisms that can decay these products do exist. Wool is made of keratin and its deterioration is due to enzymes (Fang *et al.*, 2013). Therefore, the standard test for natural durability of wood is not applicable and new methods should be developed.

5.3.6 Determination of durability by laboratory accelerated testing

Research work dealing with natural durability may potentially provide general information for the technical evaluation of lesser-known wood species with a specified botanical origin. However, commercial interest in natural durability tests is increasing, taking into account the use class for assessing performance. Wood trade organisations and many companies are now demanding detailed information on the natural durability ranking of commercially available timbers. These can differ from the standard wood species as listed in the European standard EN 350-2 (CEN (1994b)). In this standard, the natural durability was referred to forest species or autochthonous wood species. However, in the last decades, the increase of wood breeding programmes for wood utilisations in zones of different latitude and climatic conditions than the original areas causes high variability in natural durability of wood species and sometimes major deviations from original EN 350 data.

Furthermore, the natural durability classification of wood is basically related to the performance and service life whilst in contact with the ground. This is in contrast with wood used in the building sector where ground contact is often avoided, except for utility poles and railway sleepers.

This parameter is evaluated by means of 'graveyard' testing or can be derived from experiments mainly in comparison with other wood species. According to the European standard EN 350-1 (CEN (1994a)), the natural durability of wood is defined as 'the inherent resistance of wood against various wood-destroying organisms'. When compiling the European standard EN 350-2 (CEN (1994b)), which lists the natural durability for wood species, a shortage of reliable test data was noted. This lack of knowledge was also dominant when considering lesser-known tropical wood species, which have recently been introduced into the timber trade of industrialised countries. Following this, a debate has arisen about the use of tropical hardwoods and fast-growing timber produced in man-made forests and is currently being discussed in different countries of Western Europe. The impact of these facts emphasises the growing need for alternative timbers, which can substitute acknowledged durable species. The conducted research has been initiated to evaluate laboratory fungal tests on their ability to determine the natural durability of wood.

Using classification systems for natural durability based solely on fungal testing is only relevant when the risk of termite attack on wood may be excluded. Classifications for durability against fungi and termites are different and can be considered independent from one another. Laboratory testing creates a situation, which may be defined as unnatural, and therefore, the results should be used comparatively. Since most trials are carried out in small containers using basidiomycete fungi as the sole test organisms under sterile conditions, no interaction between the fungal species and other types of microorganisms can take place as happens in field trials and many other situations in which timber is used in practice. Natural ecosystems, such as unsterile soil, better allow for biological interaction. Nevertheless, laboratory tests give relative information on durability, provide results quickly and allow for the resistance assessment of a wood species. Anyhow, most wood for construction is used out of ground contact, and the laboratory test conditions are harsher (worst-case scenario) than those to which the wood commodities will be exposed during their service life.

Long-term field stake test methods like the European standard EN 252 (CEN (2014a)) are well established for testing the natural durability of timber in contact with the ground. This study has applied a method for accelerated testing of the natural durability using soil as a substrate (ENV 807, ENV, 2001). ENV 807 test results can be difficult to transfer to field conditions as this standard excludes basidiomycete decay that is present in ground contact, and hence, some authors propose to use more laboratory simulation testing including Basidiomycetes like terrestrial microcosms (Edlund and Nilsson, 1998).

5.3.7 Test methods

Laboratory test methods to assess natural durability have existed for a long time, for example, Humphrey (1916), but the commercial interest to classify lesser-known wood species and modified wood increased over the last decades. This was underlined when collaborative research was initiated as reported by Willeitner and Peek (1997).

In Europe, the natural durability of wood may be examined through laboratory testing methods according to the European standard EN 350-1 (CEN (1994a)). This standard describes laboratory methods for the evaluation of the natural durability based on a basidiomycete test (according to EN 113 (CEN (1996)) – agar-block test) and a soft-rot test (according to ENV 807 – soil test). The test methods provided in standard EN 350-1 (CEN (1994a)) are based on the test methodology as summarised by Bellmann (1988a,b). A key element remains how to transform such decay test results into durability classes. An initial method for interpreting durability from mass loss figures is to use classes related to the absolute figures. Originally, these figures were averaged for all fungi used when testing wood species (Cartwright and Findlay, 1958). More recently, the mean of the two fungi causing the highest mass losses was used for converting absolute decay figures in durability classes (Princes Risborough Laboratory, 1972). Another issue that should be considered is that the virulence of fungi is not constant. Hence, expressing the mass loss of a tested wood species to a reference species with a low durability seems to be more appropriate. Depending on how such a relative approach is used, it might be necessary to reevaluate the limits established for the durability classes. According to the standard CEN/TS 15083-1 (CEN (2005a)), the highest absolute mass loss values should be used to classify resistance against Basidiomycete fungi (brown rot and white rot) shown in Table 5.4, whilst in CEN/TS 15083-2 (CEN (2005b)), *x*-values are used to assess impact of soil inhabiting microorganisms (soft rot) as detailed in Table 5.5.

Laboratory testing of natural durability is intended to be far more reproducible and deals with specific modes of action of components present in durable wood species.

Table 5.4 Durability rating scale, according to CEN/TS 15083-1 (CEN (2005a))

Durability class	Description	Percent loss in mass
D1	Very durable	≤5
D2	Durable	>5 to ≤10
D3	Moderately durable	>10 to ≤15
D4	Slightly durable	>15 to ≤30
D5	Not durable	>30

Table 5.5 Durability rating scale, according to CEN/TS 15083-2 (CEN (2005b))

Durability class	Description	*x*-value[a]
D1	Very durable	≤0.10
D2	Durable	>0.10 to ≤0.20
D3	Moderately durable	>0.20 to ≤0.45
D4	Slightly durable	>0.45 to ≤0.80
D5	Not durable	>0.80

[a] For hardwoods, the *x* values are calculated with the following equation: $x = \frac{\text{median value of mass loss for timber test specimens}}{\text{median value of mass loss for reference timber test specimens}}$. For softwoods, use losses of modulus of elasticity (MOE).

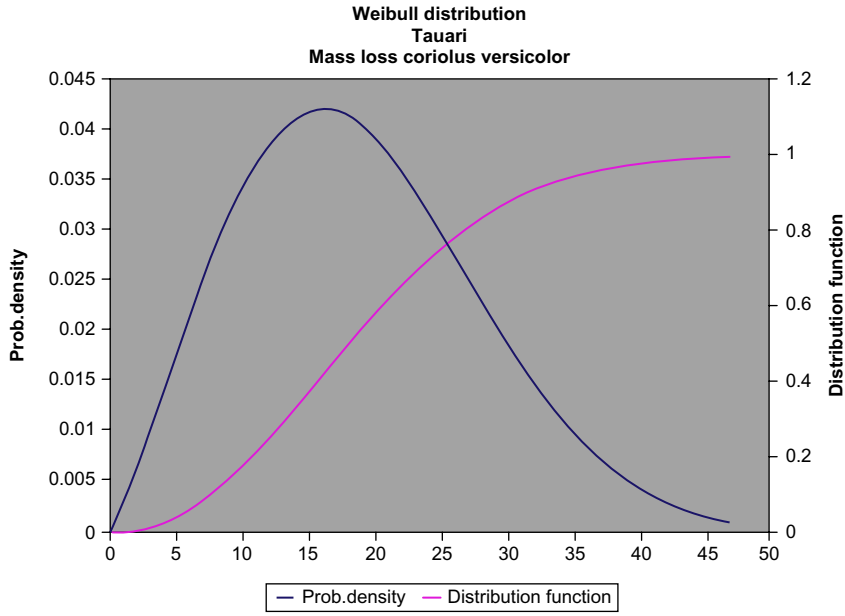
Unfortunately, different test fungi and related vulnerability differences of softwood and hardwood can lead to different severity of durability classes. An option could be to use reference wood species or wood products for the different durability classes. Typical wood species for the five durability classes that might serve as reference are presented in Table 5.6.

Van Acker *et al.* (2010) indicated that variability in resistance against fungal decay by individual test specimens mostly requires to allocate different durability classes for one wood species tested. The example for tauari (*Couratari* spp.) presented in Fig. 5.14 shows that individual blocks can be attributed to nearly all of the durability classes.

In EN 350-1 (CEN (1994a)), it is also stated that when long-term field-test data from a temperate climate site are available, they should take precedence over the data acquired from laboratory tests. For durability assessment in relation to in-ground contact use (UC 4 according to EN 335), the traditional test method as described in EN 252 (CEN (2014a)) corresponds to the original approach for durability classification. For out-of-ground contact exterior uses (UC 3 according to EN 335 (CEN, 2013a)),

Table 5.6 Typical wood species for the durability classes based on *Basidiomycete* testing

Durability class	Softwood	Hardwood
D1	Alerce (*Fitzroya* sp.)	African padauk (*Pterocarpus soyauxii*), afzelia (*Afzelia bipindensis*), and tatajuba (*Bagassa guianensis*)
D2	Western red cedar (*Thuja plicata*)	Basralocus (*Dicorynia guianensis*), oak (*Quercus* sp.) and wengé (*Millettia laurentii*)
D3	Douglas fir (*Pseudotsuga menziesii*)	Cupiuba (*Goupia glabra*), sapele (*Entandrophragma cylindricum*) and walnut (*Juglans nigra*)
D4	Spruce (*Picea abies*)	Curupixa (*Micropholis* sp.), okoumé (*Aucoumea klaineana*) and limba (*Terminalia superba*)
D5	Sugi (*Cryptomeria japonica*)	Beech (*Fagus sylvatica*), poplar (*Populus* sp.) and rubberwood (*Hevea brasiliensis*)



Wood species	Fungus	Med(*X*)	$r_{0,1}$	$r_{0,9}$	%D1	%D2	%D3	%D4	%D5
Tauari (*Couratari* sp.)	*COR*	18.2	7.6	31.7	4.2	13.2	19.4	50.3	12.9

Fig. 5.14 Weibull distributions of mass loss (%, *x*-axis) and durability classes for the medium durable hardwood tauari (*Couratari* spp., Lecythidaceae).

several attempts to use the EN 330 (CEN (2014b)) L-joint test for coated timber or even modified to be an option to test non-coated timber (Van Acker and Stevens, 2003) were not always producing equally relevant results, due to the impact of moisture dynamics. Several setups have been used to assess durability related to use class 3, all showing specific moisture dynamic parameters, for example, methods early on assessed by Highley (1995), Carey *et al.* (1981) and Militz and Bloom (2000) and compiled in an overview by Råberg *et al.* (2005). Evans *et al.* (2008) showed that a ground proximity results in an altered classification for many wood species.

To assess the natural durability or intrinsic durability against decay fungi, five durability classes have been linked to test methodology according to CEN TS 15083-1 and CEN TS 15083-2 (CEN (2005a,b)). However, it remains feasible to distinguish between in-ground contact durability taking into account both test standards or limit to out-of-ground contact uses when only referring to data obtained from the basidiomycete test CEN TS 15083-1 (CEN (2005a)), which is using similar test methodology as EN 113 (CEN (1996)) and is intended to become part of this standard. Furthermore, related to specific climatic regions, durability can also be defined, based on testing against subterranean termites, according to EN 117 (CEN (2012b)) with mainly classification related to susceptibility. Similarly, when really focusing on insect attack without considering fungal decay, susceptibility to drywood beetles can be assessed according to specific test standards EN 46-1 (CEN, 2016b), EN 49-1

(CEN, 2016c) and EN 20-1 (CEN, 1992a). Furthermore, durability against marine borers can be assessed using the test method described in EN 275 (CEN (1992b)). All this is compiled in the new version of EN 350 (CEN, 2016a).

As indicated above for wood products and also for other glued lignocellulosic-based products like WPC, basidiomycete testing is conducted using ENV 12038 (ENV (2002)) including specific preconditioning to assess long-term performance without temporary impact of glue components or low moisture content.

5.3.8 Statistical analysis

Contrary to man-made materials, wood and wood products and other natural fibre or non-wood lignocellulosic materials have an inherent variability also expressed in the intrinsic or even enhanced durability. Van Acker *et al.* (1999, 2003) underlined this, when data were compiled for the introduction of the basidiomycete test methodology to determine natural durability CEN/TS 15083-1 (CEN (2005a)). Variability can also be a parameter to assess whether a wood species or modified material is fit for purpose (Van Acker *et al.*, 2010, 2011).

Durability is considered critical for SLP and is an important topic in wood research, especially with regard to the construction product regulation (*CPR*). Both laboratory tests and in-service performance testing are therefore essential, in combination with proper monitoring and analysis tools. A crucial concept is variability and the incorporation of variability in tests and analysis, especially for a biological material such as wood. The larger the sample size, the more representative this is for the entire population, yet the number of samples is often limited by a financial upper limit. Therefore, it is essential to use the suboptimal amount of data and assess as accurately as possible the characteristic under study. De Windt *et al.* (2013) focused on the use of pdf. The principles and guidelines for pdf fitting were explored as well as the use of confidence intervals. The theoretical concepts were applied to mass loss data of fungal laboratory tests, in such a way as to illustrate intra- and interspecies variability and interlaboratory variability.

Van den Bulcke *et al.* (2013) used the concepts of pdf fitting for time-to-failure analysis of in-field tests. Both laboratory tests and in-service performance testing are therefore essential, in combination with proper monitoring and analysis tools. Sound results can be obtained, even if data are censored; that is, when for some samples, the time-to-failure criterion has not been reached or when the exact date of failure is not known, for example, due to non-continuous monitoring, which is normally the case for field testing. This methodology proved to be effective when applied on a long data set (Van den Bulcke *et al.*, 2014).

5.3.9 Position of wood products as construction material

Wood is a biological material that has always been neglected with regard to engineering quality. Contrary to metals, plastics, ceramics and other man-made products, the biological nature of wood makes it far more heterogeneous, whilst its hygroscopic nature also makes it much more influenced by moisture. The impact of moisture links not only with biological degradation but also with mechanical performance of the wooden composite structure. An attempt to integrate suitable evaluation of wood in general

with regard to biological hazard or risk is the only way to combine requirements with building options that also take into account several other performance characteristics. It is not realistic to focus only on commodity testing when biological hazard is concerned. However, commodity simulation in an overall evaluation schedule based on the final product envisaged will be essential for wooden products to remain successful in the future. Integration towards a harmonised standard including *CE* marking is a way forward for many wood products. Wood and wood products and products based on other lignocellulosic resources are important, because they are renewable. The end-of-life related to biological degradation is inherent to the fact it is part of a cyclic ecosystem but can be controlled and managed. The potential to use wood products is related to the inherent or enhanced durability or resistance, and the moisture dynamic characteristics in relation to the level of specific circumstances deviate from the forest ecosystem in respect of microclimate and presence of biological degrading organisms.

5.4 Moisture performance

C. Brischke [*,†]
[*]Leibniz University Hannover, Hannover, Germany
[†]University of Göttingen, Göttingen, Germany

5.4.1 Bio-based building materials and moisture

Most bio-based building materials such as lignocellulose are hygroscopic and tend to absorb water molecules from the surrounding atmosphere. Moisture can therefore refer to bound water that is absorbed on the interior surface of the material or free liquid water filling pores.

The material moisture content *MC* is the ratio of water taken up by a material and its dry mass and can be calculated as follows (Eq. 5.1):

$$\mathrm{MC} = \frac{\left(m_w - m_0\right)}{m_0} \times 100\left(\%\right) \tag{5.1}$$

where MC is the material moisture content (%); m_w is the wet mass (g); m_0 is the oven-dry mass (g).

The material moisture is in equilibrium with the air humidity through sorption processes. The interrelationship between relative humidity (RH) and equilibrium moisture content (*EMC*) of a material is usually presented as sorption isotherm diagrams. Hereby, one needs to distinguish between adsorption and desorption since the EMC differs between moistening and drying. The difference between the two MC values is called hysteresis and can be explained through the different mechanisms when pores of different shape and size are filled and emptied, respectively (Merakeb *et al.*, 2009; Engelund *et al.*, 2013).

Starting from the fresh state of a plant, the MC decreases during drying until free water has been fully evaporated, but bound water is still entirely remaining. This particular state is called the 'fibre saturation point *FSP*' but is never reached under

real-life situations since moisture equilibrium needs enormously long time periods to become fully established, particularly when close to the FSP (e.g. Cousins, 1978; Engelund *et al.*, 2013). Therefore, it might be considered rather as a dynamic balance.

However, within the hygroscopic range between absolute dry state and fibre saturation, many different wood properties are significantly affected by moisture changes, such as swelling and shrinking, strength as well as rheological properties, and electrical, thermal and acoustic properties. Above FSP, the cell lumens are filled with liquid water, which does not further affect the properties of the cell walls, but for instance growth conditions of decay organisms and hydraulic and electrical properties of the entire tissue including voids and cell lumens (Lin, 1967; Böhner *et al.*, 1993; Kabir *et al.*, 1997; Huckfeldt and Schmidt, 2006; Brischke *et al.*, 2014a; Stienen *et al.*, 2014).

Moisture transport depends on the material, the anatomical direction, the actual moisture content and other factors (e.g. Arfvidsson, 1998; Time, 1998; Krabbenhøft, 2003). Engelund *et al.* (2013) provided a comprehensive review on established knowledge about wood–water relationships and more recent findings. They also put into context new findings on wood–water interaction that can be at least partly transferred to other lignocellulosic materials. In the hygroscopic range, moisture transport is governed by vapour diffusion on the porous system, sorption and diffusion of bound water (e.g. Krabbenhøft and Damkilde, 2004). Beyond FSP and when lignocellulose is partly submerged in water or is in direct contact with liquid water, capillary suction plays an increasingly important role.

Apart from wood and bamboo that form more or less solid, but porous bodies, many other bio-based building materials have a fibrous structure and consist of small single elements that are used as a conglomerate. Furthermore, treated bio-based materials and composites contain extrinsic substances that can be more or less hygroscopic than the organic material itself. Consequently, to describe the MC of chemically modified solid wood and fibres, wood-polymer composites, reed, straw or hemp, further aspects need to be considered.

With respect to polymer composites and chemically modified lignocellulose, one can distinguish between the material MC and the MC of the organic substance. Therefore, knowledge about the constitution of the specific material is required, for example, the polymer percentage of a composite or the weight percent gain (*WPG*) of a chemically modified material. Apart from changes in mass, the impregnation with modification agents can also lead to changes in sorptivity. Similar effects can be observed when organic materials are impregnated with preservatives, for example, different salts with high sorptivity (Winandy, 1995; Lesar *et al.*, 2009; Humar *et al.*, 2015).

The moisture performance of materials that are usually applied as conglomerates rather than single elements strongly depends on the moisture content of the entire conglomerate. Capillary suction can be expected; for instance, when reed bundles are used for thatching (Kirby and Rayner, 1989; Anthony, 1999; Greef, 2015) or fibres are used for insulation in wall cavities (Kymäläinen *et al.*, 2001; Tavisto *et al.*, 2003).

5.4.2 Moisture sources

Moisture is more or less omnipresent since water molecules can be absorbed from surrounding air, but relative humidity of the air is affected by the season, daily temperature variations, heating regimes within buildings and several other factors. Materials

Fig. 5.15 Moistening of wood due to precipitation. *Left*: Melting snow on an oak timber bridge railing in Ahausen, Germany. *Right*: Door portal in Valparaíso, Chile, with severe damage due to moistening from splash water.

can also get wet in direct contact with liquid water. In first instance, precipitation in various forms such as rain, hail or snow has the potential for wetting as shown for melting snow on an oak timber railing in Fig. 5.15. Wood used outdoors without shelter is therefore frequently exposed to precipitation, which can be intensified in the form of wind-driven rain (Nore *et al.*, 2007; Abuku *et al.*, 2009; Barreira and de Freitas, 2013) and splash water (Glass and TenWolde, 2007; Bornemann *et al.*, 2014) as shown for a wooden door portal in Fig. 5.15.

Almost permanent wetting is provided if organic materials are in direct contact with freshwater, sea water or moist soil. The European use class (UC) system according to EN 335 (CEN (2013a)) does not distinguish between exposure to fresh water and soil contact, although the use classes are defined through moisture conditions and potential degrading organisms in a specific use condition. Apart from the moisture regime, both exposures are different in terms of direct accessibility of the materials for degrading organisms. In soil, the material is directly in contact with established fungal mycelium, nutrients and at least most often with high moisture. Therefore, posts and poles are often protected from direct contact to soil using waterproof barriers such as bituminous foils, as shown in Fig. 5.16. In contrast, organic materials exposed to fresh water are in contact with liquid water that leads to moistening, but also inhibits access of oxygen. Consequently, damage due to decay fungi requires infestation through airborne fungal spores.

Exposure to sea water involves further biotic agents that can cause severe damage to structures made from organic materials. In dependence of salinity of the water, marine borers, such as shipworms or gribble, do occur and attack structures made from

Fig. 5.16 Wood in contact with water and with the ground. *Left*: Wooden poles in sea water contact leading to moistening, mechanical loads due to moving sheets of ice and direct exposure to marine borers (Timmendorf – Poel, Germany; Photo, J. Wolff). *Right*: Utility pole in Hannover, Germany, protected from direct soil contact using bituminous foil.

lignocellulosic materials. In addition, exposure in the sea and other larger waters is associated with mechanical loads caused by floating ice sheets (Fig. 5.16) and eroding gravel in breakwater (Williams *et al.*, 2005).

Bio-based building materials can also be subject to moistening when exposed indoors or in the building envelope. Leaky pipes, roof membranes and other elements that protect a building from the outdoor environment such as windows, doors and claddings have the potential to cause severe wetting of load-bearing elements and insulation materials such as mineral wool or organic fibres. In contrast to wetting outdoors, the event of moistening indoors is usually unexpected, and therefore, measures for draining and redrying are not provided. Direct contact between inorganic materials that got wet and organic materials can lead to moisture-related problems with the latter even though it might be rather remote from the leakage.

Furthermore, frequent cleaning for instance of flooring can involve significant ingress of water and cleaning liquid, respectively. Improper cleaning can therefore lead to moisture accumulation inside the flooring and increased air humidity. High relative humidity inside of buildings in combination with the transport of humid air from the interior to the exterior can lead to condensation problems if wall mounting is incorrect. However, both condensation and leakage do also occur outdoors as shown exemplarily in Fig. 5.17 by a leaky bridge deck sealant and mould growth of algae on a cladding due to condensation moisture.

Fungal decay is one of the most prominent risks for all bio-based building materials and requires particular notice. It is commonly agreed that the moisture conditions for decay fungi become critical when free water is available exclusively in the cell walls, but not in the cell lumens anymore. It is assumed that decay fungi require liquid water for transporting degrading enzymes, and therefore, the moisture content of wood and

Fig. 5.17 Moisture ingress due to leakage. Moistened bearing of a pedestrian timber bridge in Vaxholm, Sweden, due to defect sealant of the deck.

other lignocelluloses needs to be above fibre saturation. However, results from several studies indicated that the minimum threshold MC might be significantly below fibre saturation (e.g. Zelinka *et al.*, 2008, 2015; Stienen *et al.*, 2014; Meyer and Brischke, 2015). The actual thresholds depend on particular exposure conditions, for instance, the accessibility of an external moisture source (e.g. moist bricks or insulation material), the availability of nutrients, the substrate and the decay organism itself.

Ammer (1963) used pre-infected wood specimens and stored them in different climates. Within these experiments, drastic differences were observed between the expected wood MC (EMC at given climate) and the actual wood MC after incubation of samples that showed significant mass loss (*ML*). This difference was explained by the author through the amount of water that originates from fungal metabolism, that is, the respiration of wood cellulose. Consequently, fungal decay itself needs to be considered as a moisture source as well.

5.4.3 Effects of moisture on other material properties

Initially, the uptake of water by organic building components leads to an increase of weight, which is not trivial due to its effect on dead loads in load-bearing structures. The service class system according to Eurocode 5 (EN 1995-1-1, CEN (2004a,b)) accounts for this effect. Service conditions are defined according to climate for assigning strength values and for calculating deformations of structural timber members under defined environmental conditions.

Secondly, rheological and strength properties of organic materials are affected by moisture. In the hygroscopic range strength, hardness and moduli of elasticity, shear and torsion do generally decrease with increasing moisture content (Gerhards, 1982; Green *et al.*, 2010; Dhakal *et al.*, 2007). However, highest strength of lignocellulose can be expected slightly above the oven-dry state, because at approximately 5%–7% MC,

prestresses and stress peaks are relaxed (Küch, 1943). Above fibre saturation, uptake of liquid water into the cell lumens does usually not affect the strength of lignocelluloses but can lead to so-called hydraulic effects due to the incompressibility of not only liquids such as water but also oils and waxes (Ulvcrona, 2006; Brischke *et al.*, 2014a).

Moisture uptake and release of hygroscopic materials come along with dimensional changes. Swelling and shrinking are basically caused by water molecules squeezing in between carbohydrates such as hemicelluloses and cellulose. Therefore, dimensional changes depend on the anatomical direction, the orientation of fibrils within cell wall layers and the chemical constitution of the cell wall. Wood and other lignocelluloses suffer from anisotropy, which can lead to uneven dimensional changes and corresponding deformation of building elements. In this respect, the functional performance of doors and windows can be compromised due to insufficient accuracy of fit. When forces due to swelling or shrinkage overrule the strength of the material in one direction, it can happen that cracks and checks occur in the orthogonal direction as shown in Fig. 5.18. for a bamboo screen fence and a hardwood deck. In addition to anisotropy, crack formation is influenced by the dimension of the component. A study on differently sized test specimens made from Norway spruce and Scots pine sapwood has shown that the number and size of cracks increased with increasing specimen volume (Mehlich, 2009). Besides optical appearance and mechanical characteristics, it is assumed that the formation of cracks also influences durability (e.g. De Groot and Highley, 1995).

Moisture in terms of precipitation can also have a direct mechanical effect on the structural integrity of building components. Due to recurrent impact of water in combination with other solid particles and wind forces, the material becomes an object of surface erosion. Generally, erosion does not affect the strength of building components in a notable manner but can occur unevenly and therefore affect the surface quality of bio-based building materials. Fig. 5.19 shows an example of end-grain erosion where the effect of density on erosion rates (Sell and Feist, 1986) becomes clearly visible between earlywood and latewood.

Various bio-based fibres are appreciated insulation materials due to their low thermal conductivity combined with fluffy structure (Kymäläinen and Sjöberg, 2008).

Fig. 5.18 Formation of cracks due to swelling and shrinkage. *Left*: Bamboo screen fence in Alsfeld, Germany. *Right*: Robinia deck in Bordeaux, France, showing extreme three-dimensional deformation.

Fig. 5.19 *Left*: Reduced adhesion of coatings. Flake offs of coated balcony railing in Eksjö, Sweden. *Right*: Erosion of earlywood portions on the end grain of thermally modified spruce boards after 10 years of outdoor exposure in Ahausen, Germany.

However, thermal conductivity is strongly affected by moisture and increases with increasing moisture content (Sonderegger and Niemz, 2009; Vololonirina *et al.*, 2014). Consequently, moisture accumulation in the insulation layer of exterior walls does not only involve the risk of fungal infestation and mould growth but does also reduce the thermal performance of a building and its components.

Furthermore, as shown exemplarily in Fig. 5.19 for a coated balcony railing, wetting can lead to adhesion problems and flake offs of coatings or opening of glue lines. Subsequently, moisture can accumulate since the remaining and still intact coating inhibits redrying of the respective commodity. The negative effects of defect coatings can be used to promote decay as for instance done in durability tests for coated window joinery with the L-joint tests (EN 330, CEN, 2015b; see also Section 7.3.1).

Finally, moisture is an essential requirement for the colonisation of natural building materials and a prerequisite for their biodegradability. For instance, the surface layer of roofs made from wooden shingles or thatched with reed or straw frequently shows superficial growth of algae, lichens and mosses in particular when shaded by neighbouring trees (Singh and White, 1997; Brischke *et al.*, 2016). Such superficial layers – also named 'biofilms' – do not necessarily have a negative effect on the substrate below, which can also be inorganic. Other substrates such as concrete, stone, brick, gypsum, polymers, coatings or metals are also colonised by microorganisms if the climatic conditions are favourable and form biofilms that can lead to discolouration and eventually accelerate degradation (Gaylarde and Morton, 1999). Biofilms are usually slimy layers (films), where bacteria, algae, fungi or protozoans are colonising on the interface to solid building materials (Fig. 5.20). However, biofilms can also have positive effects on the colonised substrate, since they can serve as protective shell inhibiting infestation with degrading organisms such as decay fungi due to competitive or antagonistic effects (Sailer *et al.*, 2010; Filippovych *et al.*, 2015). Anyhow, biofilms usually come along with a wet surface, whereby it is not always clear if wetness was the reason for or consequence of the superficial growth (Brischke *et al.*, 2016).

Fig. 5.20 Moisture-induced colonisation of wood by organisms. *Left*: Railing of oak timber bridge covered by a biofilm and partly renewed elements. *Right*: Wooden flooring severely attacked by *Serpula lacrymans* (Photo: L. Meyer-Veltrup).

The growth of mould fungi is also a superficial phenomenon but considered more harmful compared with the discolouration by staining fungi or the formation of biofilms since it involves the risk of allergic reactions. People living in houses with severe incidence of mould fungi can become sensitised to mould spores and suffer from serious health problems (Piipari and Keskinen, 2005; Koskinen *et al.*, 1999). Mould growth is always associated with high humidity interior and exterior as highlighted more in detail in Section 8.2. Similarly, moisture is a key factor also for staining and lignocellulose-degrading fungi, whereby the moisture requirements can differ between groups of fungi and even between fungal species within one systematic group (e.g. Huckfeldt and Schmidt, 2006; Isaksson *et al.*, 2010; Viitanen *et al.*, 2010; Vereecken and Roels, 2012; Meyer and Brischke, 2015). For various reasons, moisture can ingress in buildings and cause severe damage to organic materials (Fig. 5.20), not only to wood but also to textiles, leather and various composites.

5.4.4 Measures for quantifying moisture performance

As evident from the numerous effects that moisture and moisture-induced properties can have on the performance of organic building materials, different procedures are conceivable for quantifying moisture performance.

The moisture content (MC) as expressed through Eq. (5.1) is affected by climatic changes, and therefore, one-point-in-time measurements do usually lack comprehensive information. Nevertheless, average MC over time might give an indication with respect to the *ToW* and can be used for quantifying the 'relative moisture performance' (Isaksson and Thelandersson, 2013) of construction details and for comparative studies with different materials. Several direct and indirect methods are available to measure material MC and can be applied in laboratory and under field or in-service conditions for moisture monitoring. MC itself can serve as input variable for modelling moisture

performance in terms of time-series analysis (e.g. Van den Bulcke *et al.*, 2009). Alternatively, MC can be one of the several input variables for more complex models (e.g. decay models; see Chapter 8; Isaksson *et al.*, 2013), and moisture-induced dosage is accumulated over time to predict a response in terms of performance, that is, durability, functional or moisture performance.

Independent from the way MC values are used and further processed for analysing *ToW*, one needs to carefully select the region of interest *RoI* (Li *et al.*, 2013), that is, the position of the measuring points. If one aims on investigating the moisture-induced risk for structural failure, decay or discolouration, frequently, the material climatic conditions are monitored (Brischke *et al.*, 2008) to quantify the 'critical in situ conditions' as defined by Gobakken *et al.* (2008).

Usually, the RoI is rather small compared with the entire building and its components under test wherefore point measurements are needed, by using electrical or hygroscopic bore-hole measurements that allow determining local MC. In contrast, gravimetric measurements are used to determine only global MC, that is, the MC of the entire element that is weighed.

In other cases, it is recommended to determine the moisture-affected measure instead of the MC itself, such as moisture-induced stresses on load-bearing structures (Tannert *et al.*, 2011; Fortino *et al.*, 2013), dimensional changes of modified wood products (Welzbacher *et al.*, 2008) or colour changes due to discolouring organisms (Fabiyi *et al.*, 2008). Since many material properties are affected by moisture exclusively in the hygroscopic range, one needs to distinguish between bound and free moisture, which is generally impossible with MC measurements. As illustrated by Meyer *et al.* (2012), acetylated wood shows dramatically high MC when exposed outdoors due to increased capillary water uptake, but does not suffer from an increased moisture-induced risk for decay, because water uptake takes place only in cell lumens, and wood cell walls stay unaffected.

Moisture performance tests in the laboratory can include liquid or vapour water uptake and release over short, medium or long terms (Van Acker *et al.*, 2014a–c; Brischke *et al.*, 2015). Capillary water uptake, adsorption and desorption need to be considered for predicting outdoor moisture performance of wood and other organic building materials (e.g. Rapp *et al.*, 2000; Van den Bulcke, 2011; Brischke *et al.*, 2015).

5.5 Aesthetics

A. Sandak, J. Sandak
CNR-IVALSA, Trees and Timber Institute, San Michele all'Adige, Italy; University of Primorska, Koper, Slovenia

5.5.1 Definition and function of aesthetics

Aesthetics is the branch of philosophy that deals with the nature and expression of beauty. The word is derived from the ancient Greek *αίσθητικός* meaning 'sensitive, sentient pertaining to sense perception'. Aesthetics is an expression of taste, which is essentially a preference. Taste not only is personal but also subjects to social influences.

Aesthetics is one of the major principles in architecture and it concerns to appreciation of beauty. It is usually accomplished by the shape, colour, contrast, type of material, symmetry and simplicity of the repeated pattern used in design. The key elements regarding aesthetics in architecture are related to mass and space, proportion, symmetry, balance, contrast, pattern and decoration.

When the material/product has been well designed, it gives the user the correct functionality and is evaluated as good. When it additionally considers ergonomics, durability and aesthetics, it may be assessed as excellent. Aesthetics and functionality are crucial for the design, but both can be uniquely different. Function is the purpose for which design is developed. Empirical aesthetics, even if considered as a relatively young science, is in fact an old subject of interest (Carbon and Jakesch, 2012). Aesthetic response is a human reaction to the artistic qualities of a sensory experience. According to Hansson (2005), satisfaction of functional requirements in most cases contributes positively to aesthetic value. Aesthetic experiences are related to the emotions gained through sensory system. These are connected with both the objective properties of materials and the subjective responses from people being influenced by the environmental context (Zuo *et al.*, 2014). The aesthetic response must take into consideration the social and economic circumstances and the materials used and technologies available at a given time.

5.5.2 Aesthetic versatility of bio-based materials

Development of innovative materials nowadays does not require any more choosing between function and aesthetics. Novel materials offer optimal performance together with satisfying aesthetic impressions. However, when considering the use of bio-materials in building environment, their appearance becomes the key issue. For that reason, it is essential to select materials that exhibit desirable appearance from a distance and from nearby and are properly integrated with the building form. Building materials must be incorporated within design process, not only for new buildings but also when retrofitting existing structures. Bio-based materials offer a wide range of appearances, starting from traditional rustic materials to modern design products. Some examples of both traditional bio-material use, such as non-protected cladding with silver patina due to natural weathering, wooden logs used for buildings and white straw or wooden shingle used for roof protection, are shown in Fig. 5.21. On the other hand, composite cladding, innovative insulation materials and thermally/chemically modified wood as used recently for siding or decking are a sign of the modern design.

5.5.3 Properties influencing perception of materials

Most aesthetic theories are consequently inspired by sense of sight (ophthalmoception or vision) and are mainly tested with regard to visual effects (Carbon and Jakesch, 2012). Aesthetic attributes such as colour and texture, together with other properties of wood products, influence consumer preference (Ramananantoandro *et al.*, 2013). In the case of building materials, those will include surface colour, pattern and gloss. The colour is an attribute related to the complex interaction of light that may be reflected,

Fig. 5.21 Various outlook of bio-based materials: rustic *(top)* and modern *(bottom)*.

absorbed, transmitted or sometimes emitted from the object surface. It is a visual perception by which an observer recognises this attribute. Colour selection is an integral part of the design process. It can affect the outlook and impression of a material. In consequence, people react to colour individually. Example of how variations of colour affect the perception of the materials is presented in Fig. 5.22. Products from the same wood species might have very different appearance when it is finished with different coating products.

Pattern is defined as a repeating artistic or decorative design. Pattern can be also described as a replicated unit of shape or form over the object, a 'frame' that organises the parts of a composition. The material itself may contain a pattern, for example, wood sections: radial, tangential, longitudinal or late/early wood distribution. Conversely, the way a material has been integrated within the structure can create a pattern as well (Fig. 5.23).

One of the most important but sometimes underestimated properties of the surface is the light reflectance or gloss. In general, there are three types of interactions when light hits a surface: reflection, absorption and transmittance. The factors that affect

Fig. 5.22 Colour variation of natural ash finished with various products (from the left: transparent varnish, preserver, stain, dye, wax, oil and paint).

Fig. 5.23 Pattern related to the material itself *(up)* and to the assembled material *(down)*.

gloss are the refractive index of the material, the angle of incident light and the surface topography. Variations in surface texture directly influence the level of specular reflection. Objects with a smooth surface (well polished or coated with finely dispersed pigments) appear shiny to the eye due to a large amount of light being reflected in a specular direction. Rough surfaces reflect no specular light, as the light is scattered in other directions and therefore appears dull.

When dealing with building materials, it is important to also include a haptic perspective (perception of materials roughness). Tactile interactions have recently become considered more often within design practice (Zuo *et al.*, 2014). The classification of products into smooth and rough may be subjective and fuzzy, without numerical quantification (Sandak and Negri, 2005). As with colour, roughness is an impression of a person, related to the sense of not only touch but also vision. Surface roughness is closely related to the material texture, which is defined as a quality of an object, which we sense through haptic senses. The texture can also be perceived as an image, suggested to the eye, which can refer to memories of surfaces previously touched.

5.5.4 Aesthetics and service life

The superior properties and the natural beauty of bio-based materials make it a desired material for various applications including construction, interior/exterior design or other uses. Unfortunately, bio-materials as any other materials are subject of deterioration due to several factors, including weathering, oxidation, biodegradation, wear or decay, among others. It is important therefore to assure the due performance of building products during their functional service life. On the other hand, it is not just the functional performance that is an issue, but it is extremely important to also consider aesthetical service life (Sandak *et al.*, 2015a).

In the last decades, increasing interest for quantification of durability and service life of materials, components, installations, structures and buildings has been noticed (Hovde, 2002). Service life is defined as the period of time after construction in which a structure maintains or exceeds minimum performance requirements without unforeseen or extraordinary maintenance or repair (ISO 15686-1, ISO, 2000). Service life of façades depends on many variables, some of which are environmental and, as a result, beyond the control of the designers and owners. It is clear that in order to maximise the general performance of building, it is necessary to achieve the optimum balance between functionality, investment costs and maintenance efforts.

5.5.4.1 Factors influences change of aesthetical properties

The most apparent aspects of wood surface affected by weathering are those related to visual appearance, such as changes in colour, roughness, surface checking, dirt uptake and growth of mould. The time of weathering is a driving variable affecting surface deterioration (Fig. 5.24). Nevertheless, there are other factors to be considered when describing the weathering mechanisms, with exposure direction and site location being the most important.

Biotic decay is another critical process affecting material functionality and aesthetics (see Section 4.2.2). The degradation might have different kinetics depending on the

Fig. 5.24 Appearance of natural and coated wood due to natural weathering for different time durations.

fungi type and consequently affect the materials' functionality and appearance in diverse ways. Insect activity might also have significant influences on the bio-materials' look. There are also several processes that influence building materials appearance that cannot be forecasted during designing phase, such as acts of vandalisms. Other impacts, such as fire, flood, storms or earthquake, even if not predictable, should be considered whilst designing.

5.5.4.2 *Methods for monitoring of changes to aesthetics appearance of biomaterials along the service life*

The most direct method for evaluating the aesthetic appearance of materials is by visual assessment. However, it possesses high degree of subjectivity whilst performed by an untrained person. The simplest approach to quantify appreciation is a semantic differential method (e.g. ugly–beautiful) as proposed by Osgood *et al.* (1957). The advancements in visual assessment are controlled tests according to clearly defined rules (e.g. focus on sample colour, detection of particular defects and other characteristics). In this case, clearly defined criteria are provided to the assessing person prior to material evaluation. The judgement should be performed with samples presented in a random order by a group of equally trained individuals. An example of the grading rules for the weathered wood samples is presented in Fig. 5.25.

Contrary to visual assessment, the measurement of surface properties/appearance with a dedicated sensor provides objective values that might be related to the current state of the material in use. Samples can be collected in the field and measured in a laboratory environment after conditioning. Nevertheless, recent developments in optics and electronics open new possibility to perform measurements directly in situ. Non-destructive techniques/instruments that do not require particular sample preparation, such as colour/gloss meters or spectrophotometers, can be

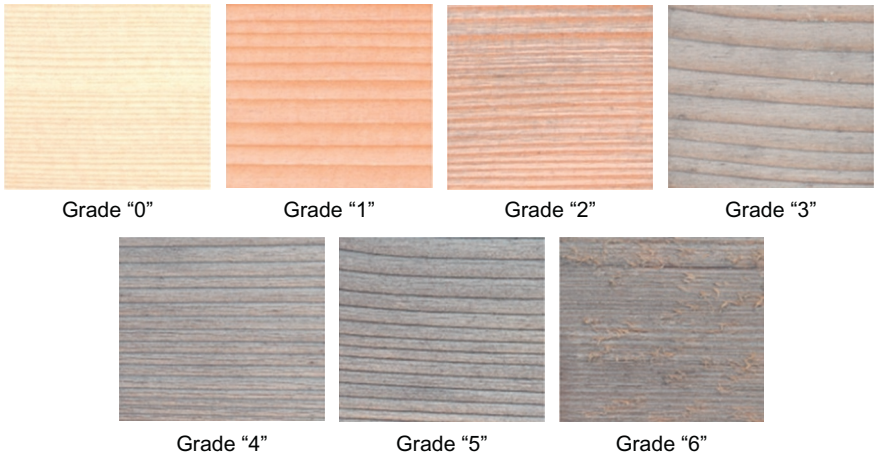


Fig. 5.25 Weathered samples corresponding to seven levels grading scale.

implemented. Such devices provide certain indicators, such as CIE L*a*b* colour, refractive index or a raw spectrum. In most cases, the above parameters provide only incomplete information about a range of aesthetical aspects. Thus, single sensors are rarely recommended for assessment, and a multi-sensor approach is more frequently suggested for applied research. The data collected by various sensors often express diverse physical phenomena that make the interpretation of results more demanding. Another challenge is therefore the combination of data provided by various sensing techniques and proper data mining. The most advantageous solution when dealing with material performance during service life is a time-resolved measurement campaign. When the material state is assessed regularly, such measurements turn into monitoring. Dedicated interfaces are indispensable for integrating signals (measurements, images, waves, spectra, etc.) generated by various sensors/systems. Such data fusion systems are rather complex, and technical solutions are case-dependent (Sandak *et al.*, 2015b).

5.5.5 Modelling of aesthetical performance

Modelling is more precisely described in Chapter 8. Respective subchapters described application of modelling in the assessing of the aesthetic performance. Bio-materials possess several advantages over alternative resources. Natural beauty makes them very attractive for several applications providing superior aesthetical impressions, microclimate comfort and environmental friendliness. The performance of biomaterials within the interior of a house is usually straightforward. However, in exterior use, natural products may lose visual appeal (due to staining, oxidation, discolouration, etc.) leading to perceives; the purpose of regular maintenance is to maintain the life of the wood product by postponing obsolescence, in terms of both aesthetic and technical requirements. As a consequence, it is critical not only to redefine the 'service life' as related to the technical performance of the structure but also to consider factors of aesthetical perception and tolerance from visual depreciation. It is relatively simple to define the critical limits when wood is losing its technical characteristics (due to decay, mechanical strength decrease, loss of dimensional tolerances, etc.). However, it is extremely difficult to define the critical limits regarding aesthetics (Sandak *et al.*, 2015a). In real cases, the aesthetic requirement limits are reached before functional loss and passing the safety level. The estimated service life end is identified therefore by considering certain constraints and depends on the critical aspect (aesthetics, function and safety) disqualifying the structure from its proper use. Fig. 5.26 presents different scenarios of service life for a building façade. The loss of structure safety is reached relatively fast when no maintenance and/or replacements are performed (Fig. 5.26, top). The service life can be substantially extended by applying proper in-time mitigating action to protect the façade, for example, by replacing damaged parts (Fig. 5.26, lower left). A regularly scheduled maintenance action allows the highest extension of the service life (Fig. 5.26, lower right). It is challenging, however, to determine optimal levels of appearance, functionality and safety limits (states of the façade), since this is a compromise between expected functional requirements, performance and operational and maintenance costs.

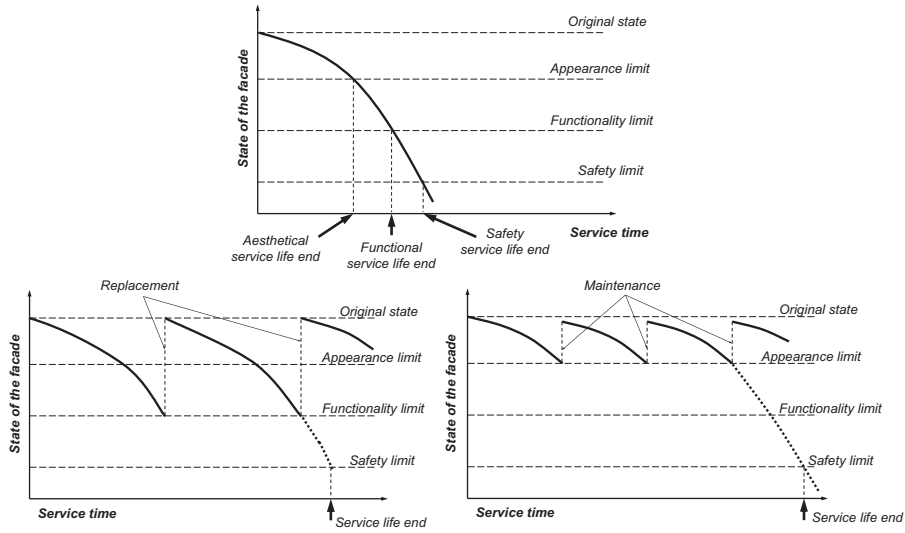


Fig. 5.26 Estimation of the service lifetime according to different scenarios; *(top)* no any repairs, *(lower left)* replacement and *(lower right)* frequent maintenance.

5.5.6 User preferences and expectations

Aesthetics play a significant role in cognitive processing. The impression of the material outlook greatly influences the way people think or perceive it. Designers must understand the tastes of the target audience and then use aesthetics to reflect those preferences. Several methods are available to verify customer preferences and measuring the material aesthetics. Sensorial analysis is an appropriate tool to study relationship between hedonistic judgement and product characteristics (Nyrud *et al.*, 2008). Hedonistic testing can be carried out with prior training of the responders or without any preparation. Selection of materials and target groups of respondents must be carefully planned in order to obtain reliable results. Tests might be performed using only visual stimuli, such as dedicated human machine interface or computer-based tests. But using real samples and employing more than only vision during their assessment (hearing, taste, smell and/or touch) is a superior alternative. Figs 5.27 and 5.28 present examples of the sample presentations during the hedonistic tests by means of only visual stimuli or by combining several sensations.

Quantification of customer choices during preference testing may be done using different approaches. The simplest requires preparation of stimuli and verification of the preferences of those responding with semantic differential methods by choosing among the following: ugly–beautiful or best–worst (Osgood *et al.*, 1957). Other methods involve the selection of a few favourite materials among a set of alternative samples representing the variability range of available choices. It is used to rank the attractiveness of materials/products and identifying the most appreciated. The variety of the investigated materials will determine the complexity of the test. Respondents might perform single- or multi-attribute comparison. The first is focused on determining a simple preference without considering the overall contest, for example, favourite

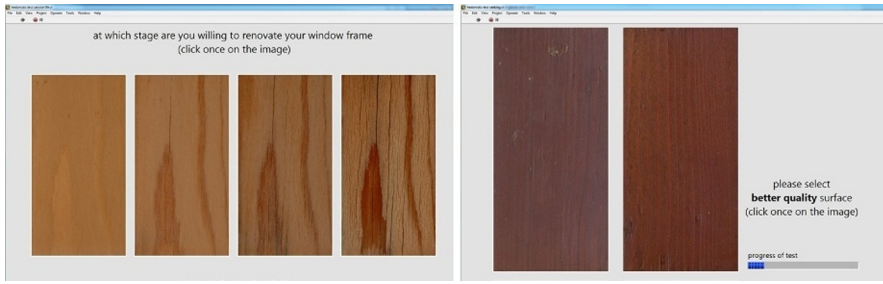


Fig. 5.27 Print screen from hedonistic test performed to verify minimal maintenance period for windows frames.

Fig. 5.28 Stand used for verifying customers' preferences by means of different senses (from top: vision, olfaction, vision and haptic perception, haptic perception and intuition-sixth sense).

wood species. Multi-attribute comparison takes place when more than one attribute is confronted simultaneously, for example, favourable wood species used for façade cladding in a certain assembly form.

Tests of preferences might be designed in a more complex way and combined with non-aesthetical factors influencing the customer choice (Sandak *et al.*, 2015c), such as economic issues (investment cost and maintenance frequency) or environmental awareness (local/imported resources or natural/modified wood).

A preference test approach can be considered as a very useful tool for scheduling of conservation/maintenance. In this case, the goal of the test is to define a limit of the customers' tolerance for surface defects due to weathering or other signs of deterioration.

5.5.7 Environmental impact of aesthetics on selection of bio-materials

In the modern society, a choice of materials for building purpose requires consideration of aesthetic appearance and investment costs, maintenance intensity, service life duration, among other factors. The life-cycle assessment considerations and the ability

to reuse, recycle or dispose of the material at the end of its life are recently considered as particularly important, due to increasing public awareness. Architects have broadly started to apply eco-friendly building materials, and it is expected that sustainable buildings become more common in the near future. Bio-based materials are undoubtedly friendly to the environment, allowing erecting of buildings through both pleasant and aesthetic design. An important concern still remains related to the bio-materials' aesthetical deterioration, varying significantly in different locations and being very much related to the construction details. In order to avoid customer disappointment, it has become important to better understand the aesthetical changes through modelling of degradation processes.

Summarising, the selection of building materials is not only related to technical/functional characteristics but also influenced by environmental impact and by visual appearance, the last being particularly essential, as stated by Norman (2002): *Aesthetics Matter*: *Attractive Things Work Better*.

5.6 Thermal performance

A. Ugovšek, B. Šubic
M SORA d.d., Žiri, Slovenia

5.6.1 Introduction

Wood has once again become one of the most important building materials in recent years and is incorporated in many new buildings due to its natural aspect, physical properties, visual attractiveness and good thermal properties. Thermal properties of wood can be divided into three main subcategories: thermal conductivity (λ), heat capacity and thermal diffusivity. λ is most commonly used for calculating insulating properties of various building parts, for example, walls, doors and windows. λ of a material is defined as the steady-state heat flow rate per unit area per unit of temperature gradient through unit thickness in the direction perpendicular to the isothermal surface (TenWolde *et al.*, 1988) and is the opposite of the thermal insulation capacity. In SI units, it is measured in watts per metre kelvin (W/m K), whereas in imperial units, λ is measured in BTU/(h ft °F). According to ISO 10077-2 (ISO (2012)), which is used for calculating of thermal transmittance (U-value) of windows, doors and shutters, timber species are divided in four λ groups (Table 5.7).

λ can be determined with various methods. The most common procedure for measuring λ of wood is the hot-plate (*HP*) method, whereas heat flow (*HF*), transient plane source (*TPS*) and modified transient plane source (*MTPS*), transient hot wire (*THW*), transient hot strip (*THS*) and transient hot bridge (*THB*) methods can also be used. Besides these methods, numerical modelling is a potential approach to analyse λ of wood. All listed methods are described later.

λ of wood is low due to its porous structure and several cell lumens filled with air. Motionless air has very low λ – 0.024 W/m K (Ngô and Natowitz, 2016), whereas cell

Table 5.7 λ **of wood species according to ISO 10077-2 (ISO (2012))**

Wood species	Thermal conductivity (λ)
Abies alba, *Picea abies*, *Picea sitchensis*, *Pinus contorta* and *Thuja plicata*	0.11 W/m K
Khaya spp., *Larix* spp., *Picea glauca*, *Parashorea* spp. (white seraya), *Pinus sylvestris*, *Pseudotsuga menziesii*, *Shorea* spp. (light red meranti), *Swietenia macrophylla*, *Terminalia ivorensis* and *Tsuga heterophylla*	0.13 W/m K
Entandrophragma cylindricum, *Entandrophragma utile*, *Eucalyptus delegatensis*, *Eucalyptus obliqua*, *Eucalyptus regnans*, *Heritiera* spp., *Heritiera utilis*, *Heritiera densiflora*, *Milicia excelsa*, *Milicia regia*, *Ocotea rubra*, *Shorea* spp. (dark red meranti), *Tectona grandis* and *Tieghemella heckelii*	0.16 W/m K
Afzelia spp., *Calophyllum* spp., *Eucalyptus globulus*, *Eucalyptus grandis*, *Intsia bijuga*, *Intsia palembanicia*, *Parashorea* spp. (Gerutu), *Pometia pinnata*, *Quercus* spp. and *Robinia pseudoacacia*	0.18 W/m K

wall substance at 0% moisture content (MC) has λ of 0.410 W/m K (Siau, 1995). Wood with less cell walls and more air-filled lumens is consequently a better insulator. At MC between 0% and fibre saturation point, wood is considered to be a good insulating material with low λ. The λ of common wood species used for timber engineering is much lower compared with concrete, metals and glass, which are viewed as the main materials currently used in construction. For example, the λ of structural softwood lumber at 12% moisture content is in the range of 0.10–0.14 W/m K compared with 216 W/m K for aluminium, 45 W/m K for steel, 0.9 W/m K for concrete, 1 W/m K for glass and 0.7 W/m K for plaster. The λ of wood is affected by several basic factors: density, MC, grain direction, fibril angle, extractive content and structural irregularities such as checks and knots and temperature (Glass and Zelinka, 2010). Wood species generally does not influence λ of wood.

5.6.2 Methods for measuring thermal conductivity

The general methods for measuring λ can be divided in two main groups, (I) steady-state and (II) transient or non-steady-state methods (Vosteen and Schellschmidt, 2003). Steady-state methods perform a measurement when the temperature of the analysed material is in complete equilibrium and does not change with time. The advantage of such methods is that a straightforward signal for analysis is obtained, but the disadvantage is that a well-engineered experimental setup is required and a longer measuring time is needed. The most common steady-state methods used for defining λ of wood are guarded HP method, pipe method, HP and HF method, of which the last two are the most common. The transient methods perform a measurement during the process of heating up. The advantage is that the measurement can be made rather

quickly (within seconds), preparation of the samples is simple and small samples can be measured. The disadvantage of these methods is that evaluation of results is rather complex (Linseis, 2016). The most common transient methods used for defining thermal conductivity of wood are TPS, MTPS, THW, THS and THB.

5.6.2.1 Hot plate (HP) method

The HP method is one of the basic steady-state methods. It can be performed either with a two-specimen apparatus or with a single-specimen apparatus. In both cases, the heat is being transferred from a guarded heater (hot plate) towards the specimen above or below the heater. The specimen is limited with a cold plate on the other side. Measurements are taken after the sample reaches the steady state (with zero heat gradient or constant heat over entire sample). This usually takes about 30 min (Buck and Rudtsch, 2006; Vosteen and Schellschmidt, 2003). The guarded HP method is presented in Fig. 5.29 and should be performed according to standards EN, 1946-2 (CEN, 1999); EN, 12667 (CEN, 2001) and ISO 8302 (ISO, 1991).

5.6.2.2 Heat flow (HF) method

The HF method uses two calibrated heat flux transducers to measure heat flux through a specimen that is placed between them (Fig. 5.30). A steady-state unidirectional heat flux is maintained by applying a given thermal gradient across the specimen. Usually, not only this method is used for λ lower than 0.01 W/m K, but also it has been successfully used for measuring λ of wood species (Yu *et al.*, 2011). This method has recently been used for measuring λ of natural plant fibres (Damfeu *et al.*, 2016).

5.6.2.3 Transient plane source (TPS) method

The TPS method, utilising a plane sensor and a special mathematical model describing the heat conductivity combined with electronics, enables the method to be used to measure thermal transport properties. It covers a λ range of at least 0.01–500 W/m K (in accordance with ISO 22007-2, ISO, 2015). The TPS method typically employs

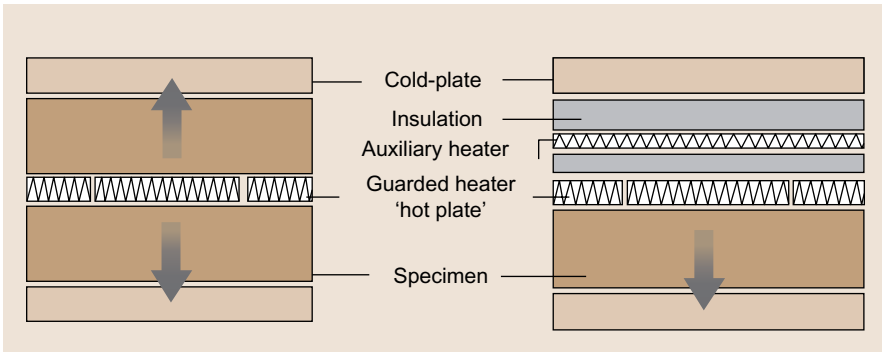


Fig. 5.29 Principle of the guarded hot-plate method with a two-specimen apparatus (A) and a single-specimen apparatus (B) (Buck and Rudtsch, 2006).

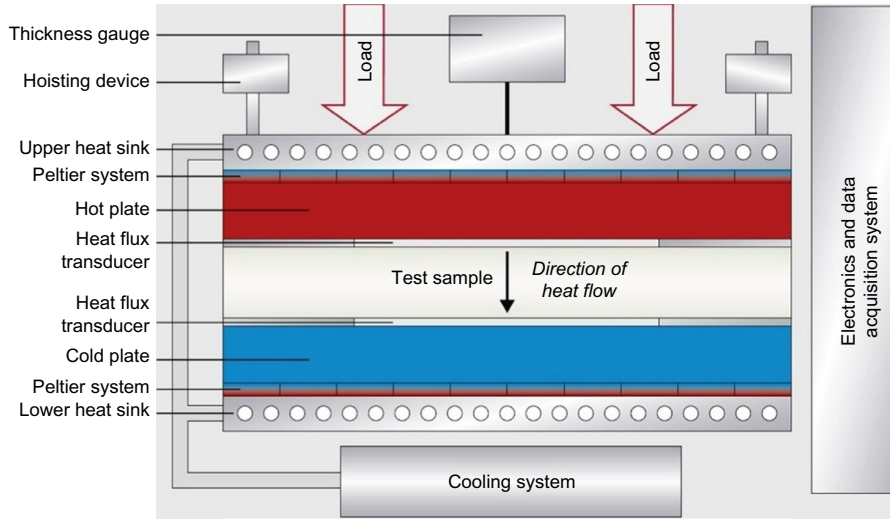


Fig. 5.30 Heat flow meter *HFM* 436/3 (Netzsch, 2016).

two sample halves in-between which the sensor is sandwiched. Normally, the samples should be homogeneous, but extended use of TPS testing of heterogeneous material is possible with proper selection of sensor size to maximise sample penetration. This method can also be used in a single-sided configuration, with the introduction of a known insulation material used as sensor support (Vosteen and Schellschmidt, 2003). Dupleix *et al.* (2012) used the TPS method (Fig. 5.31) to evaluate λ of green wood of Douglas fir, beech, birch and spruce and compared the results with the literature data and results obtained by flash method.

5.6.2.4 *Modified transient plane source* (MTPS) *method*

The device for MTPS uses a one-sided, interfacial, heat reflectance sensor (Fig. 5.32) that applies a momentary, constant heat source to the sample (Mathis, 2000). The difference between this method and traditional TPS methods is that the heating element is supported on a backing, which provides mechanical support, electrical insulation and thermal insulation. This modification provides a one-sided interfacial measurement in offering maximum flexibility in testing liquids, powders, pastes and solids.

Yu *et al.* (2011) have analysed λ dependence of MC, density and temperature for several Chinese softwood and hardwood species. Comparison between MTPS and HF method showed good correlation. It was proven that transverse λ increased with temperature, density and MC.

5.6.2.5 *Transient hot wire* (THW) *method*

The THW method is a transient dynamic technique, originally proposed by Carslaw and Jaeger (1959). It is based on a linear heat source of infinite length and infinitesimal diameter and on the measurement of the temperature rise at a defined distance

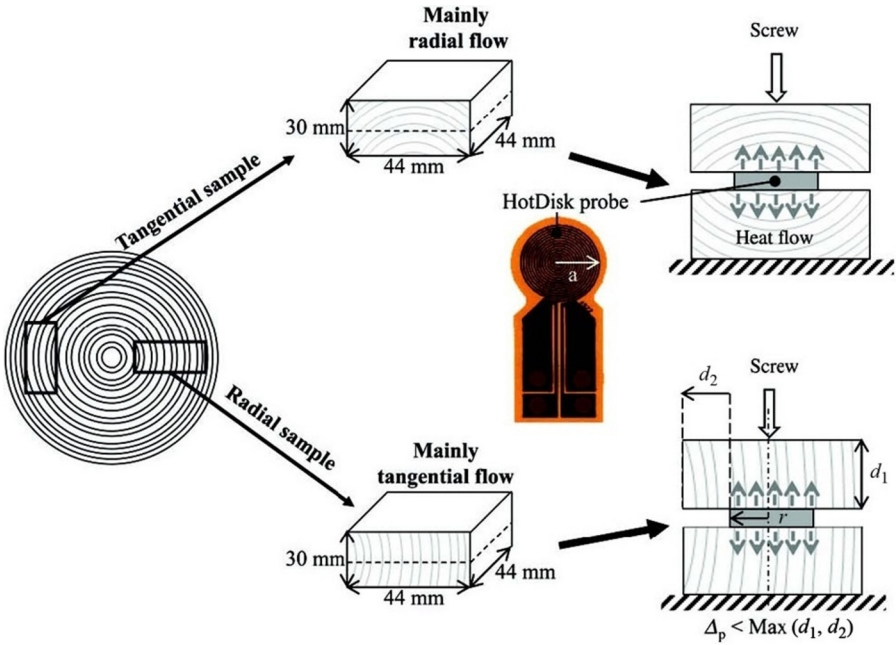


Fig. 5.31 Configuration of TPS measurement and experimental sampling (Dupleix *et al.*, 2012).

Fig. 5.32 MTPS sensor (Vosteen and Schellschmidt, 2003).

from the linear heat source embedded in the test material (Fig. 5.33). As an electric current of fixed intensity flows through the wire, the λ can be derived from the resulting temperature change over a known time interval (Franco, 2007).

Yapici *et al.* (2011) have used this method for λ measurement of Scots pine (*Pinus sylvestris*), oriental beech (*Abies bornmülleriana*) and sweet chestnut (*Castanea sativa*) for which the lowest measured value was of the Scots pine (0.18 W/m K) and the

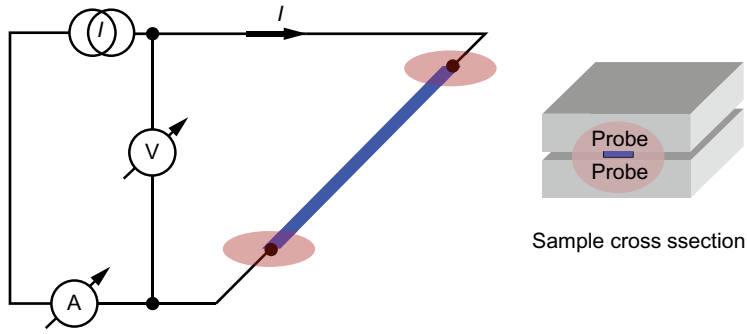


Fig. 5.33 Experimental setup (left) and sample preparation (right) (Linseis, 2016).

highest of oriental beech (0.385 W/m K). Dündar *et al.* (2012) have used the THW method to measure the λ of beech (*Fagus orientalis*), fir (*Abies nordmanniana*) and European black pine (*Pinus nigra*) and to define its correlation to mechanical properties (specific gravity, modulus of rupture, modulus of elasticity and impact bending strength).

5.6.2.6 *Transient hot strip* (THS) *method*

The introduction of the THS method was made with the specific intention of covering large ranges of λ. This has been achieved through the use of strip sizes ranging from vapour deposited microstrips to cm-wide strips made of metal foils and widely varying recording or characteristic times of the experiments (Fig. 5.34). Maximum applicability, as well as convenience, is achieved with this experimental method by using the hot strip both as a heater and a temperature sensor. It is possible to get information on the resistance increase of the hot strip by recording the voltage increase over the strip whilst it is exposed to one or several current pulses. So far, the THS (or single shot)

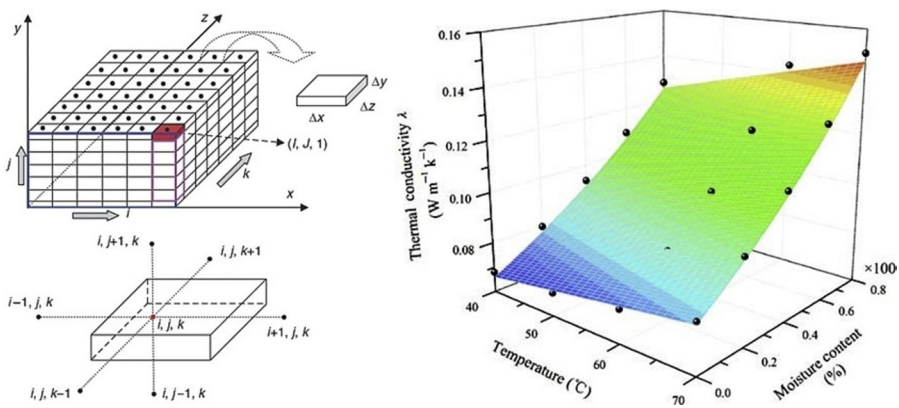


Fig. 5.34 Type of control volumes in a 3-D domain numerical model *(left)* and λ dependence as a function of the temperature and MC (Zhao *et al.*, 2016)

method has been applied to studies of a large number of different materials with λ ranging from 0.01 to 100 W/m K (Gustafsson, 1987).

5.6.2.7 *Transient hot bridge* (THB) *method*

The THB method, which is used to measure the thermal transport properties of materials, is an enhancement of the THW or the THS method (EN 993-15, CEN, 2005e). Mentioned methods are transient and time-dependent. The advantage of these methods compared with stationary methods is a much shorter measuring time, and the thermal diffusivity is measured in parallel to λ. For THS, a very thin (0.005 mm) metal strip is clamped between two cube-shaped samples in a temperature-controlled environment. An electrical heating current is then used to warm it to a constant measuring temperature, which is held for several minutes. During this time, its temperature-dependent voltage drop is simultaneously registered as the gauge for the sought transportation properties. The strip thereby serves simultaneously as heat source and resistance thermometer. The thermal and temperature conductivity can subsequently be calculated. Further development of this sensor uses a wheatstone bridge circuit instead of a heating strip, allowing the influence of the considerably lower bridge current on the measurement results to be ignored (Meinlschmidt, 2016).

5.6.3 Numerical modelling

Numerical modelling is a mathematical representation of a physical (or other) behaviour, based on relevant hypothesis and simplifying assumptions (Sirois and Grilli, 2015). It is most commonly used for civil and metal engineering but has become more common in wood science (da Silva *et al.*, 2013; Kain *et al.*, 2016), and in the last decade, it has also been used to analyse λ of wood. Most usually, numerical models describe one of the experimental methods and compare the results with those measured. In this way, the model is being validated. After the validation, parametric studies can be performed, and any variability of λ can be observed. The disadvantage of numerical modelling is the complexity of the model preparation, the exact description of the realistic problem and the evaluation of the results. The advantage on the other hand is that when a numerical model is being validated and is showing good correlation with experimental results, easy and fast observation of changing material parameters can be obtained. Zhao *et al.* (2016) have researched the λ of Dahurian larch samples (*Larix gmelinii*) in dependence of its temperature and MC (Fig. 5.35). Numerical and experimental results are showing good correlation (less than 5% difference).

Sirois and Grilli (2015) have researched the usage of numerical models for high-temperature superconductor modelling and have concluded that the main limitations for wider use of similar methods are currently the low speed performance of the models and the lack of model file templates, material data and benchmark problems. With wider availability of the last parameters, broader use of numerical models will be possible.

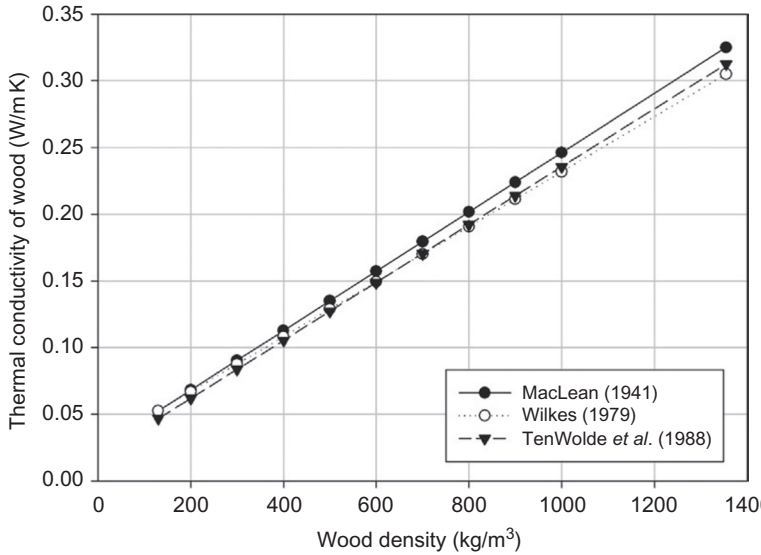


Fig. 5.35 Relationship between λ of wood and wood density at 12% MC calculated from different developed equations (MacLean, 1941; Wilkes, 1979; TenWolde *et al.*, 1988).

5.6.4 *Influence of wood properties on thermal conductivity of wood*

5.6.4.1 *Density*

Generally, λ increases as the density of wood increases. The thickness of cell walls relative to the size of lumen directly influences the density of wood and hence the availability of pathways for conductive heat transfer (Mortensen, 2007). As λ is dependent also on wood MC, the dependence of λ in wood density must always be presented at the same wood MC. Commonly, this dependence is presented either at 0% or 12% wood MC. According to Kollmann and Côté (1968), the relation between density, as well as temperature and moisture, and thermal conductivity in the direction of fibres and perpendicular to them is approximately linear in the ranges of density 200–800 kg/m^3, moisture content 5%–35% and temperature −50°C to 100°C (Sonderegger *et al.*, 2011). Different equations for calculating λ of wood based on density at specific wood MC below 30% and temperature of 25°C were developed by MacLean (1941), Wilkes (1979) and TenWolde *et al.* (1988). They are all based on linear relationship between λ and wood density (Fig. 5.35).

Even before, Rowley and Agren (1937) published results of λ based on wood density of different wood species that prove the linear relationship. λ of different wood species is nowadays determined according to different test methods (described herein), but calculated values, as presented in Fig. 5.36, are very similar to measured ones. Linear relationship between λ and wood density of several wood species was proved also by Niemz and Sonderegger (2011); Jankowska and Kozakiewicz (2013) measured selected wood species from Africa, whereas Kol and Sefil (2011)

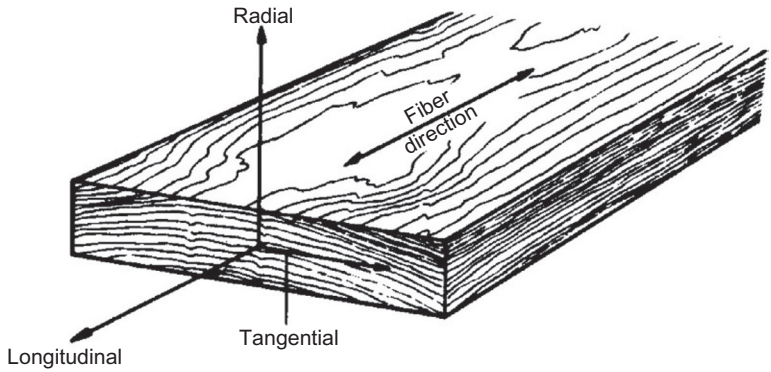


Fig. 5.36 The three principal directions of wood (TenWolde *et al.*, 1988).

measured λ of fir and oriental beech after heat treatment at different temperatures (170–212°C) and consequently different densities. However, λ decrease of thermally modified wood is rather more complicated as wood MC is additionally influenced by the intensity of heat modification, which has also important effect on λ of wood (Kanter, 1957; Steinhagen, 1977). Ugovšek *et al.* (2015) reported a passive timber window made of thermally modified spruce (*Picea abies*) where a measured λ of 0.09 W/m K was used for the calculation of thermal transmittance of window frames. Research into the influence of compressing of wood on λ was made by Asako *et al.* (2002). They found that λ in longitudinal and tangential direction increased proportionally to the density increment due to the compression, but λ in the radial (compressed) direction increased just slightly, which is desirable in terms of use for, for example, window frames.

5.6.4.2 Wood MC

Wood MC has, besides wood density, a major influence on λ. As with wood density, there is a linear correlation between λ and MC, but attention must be paid on MC below or over the fibre saturation point. Early work into this was published in 1937 by Rowley and Algren, Wangaard (1940), MacLean (1941) and later by Kanter (1957) who plotted the λ in the radial direction of birch wood over a range of −40°C to +100°C and 0%–130% wood MC (Kanter, 1957).

The linear relation between MC and λ of species grown in China was determined by Yu *et al.* (2011), but the scope of trend lines was different than that of MacLean (1941) and TenWolde *et al.* (1988). Sonderegger *et al.* (2011) also determined linear correlation of λ of Norway spruce and European beech in the radial, tangential and longitudinal directions as a function of MC with R^2 of this relationship of ~0.95–0.99. The influence of the MC on the λ was higher in the tangential than in the radial direction and very low in fibre (longitudinal) direction, which was found also for elm wood by Hrčka and Kurjatko (2006). Dupleix *et al.* (2012) measured birch and Douglas fir besides spruce and beech but of green wood at MC over 25%. Free

water conducts more heat than bound water, and consequently, the λ increment was steeper above fibre saturation point (Siau, 1971). As in case of λ below fibre saturation point, λ of wood increased linearly with MC and reached about 0.5 W/m K when MC of beech and birch was about 120%. There was no significant difference in λ between the radial and the tangential directions for wood in the green state as the presence of free water in the cell diminished any effects arising from the anisotropy of the wood. The exception was spruce, where λ in the radial direction was higher than λ in the tangential direction. This was attributed to the presence of ray cells that promote heat transfer in the radial direction (Dupleix *et al.*, 2012). The effect of MC of pine wood on λ and parallel on dielectric properties of wood was studied by Kol (2009). Results again showed that MC affected λ and dielectric properties of wood in a similar way by a linear increase of both studied parameters. Rice and Shepard (2004) made an interesting research in which λ of plantation grown white and red pine wood was measured at two MC levels. They noticed that when both species were oven dry, the λ of white pine (*Pinus strobus*) was about 10% lower compared with red pine but was equal at nominal MC of 12% even though the density of red pine was about 8% higher.

5.6.4.3 Wood orientation

It is generally known that λ in longitudinal direction (parallel to grain) is greater than λ in the transverse direction, which is correlated to the orientation of the molecular chains within the cell walls (Fig. 5.36). λ in radial direction is generally slightly higher than in tangential way, due to the influence of radially oriented wood rays (Steinhagen, 1977; Suleiman *et al.*, 1999). Radial λ can be higher for approximately 3%–20% (Sonderegger *et al.*, 2011), whereas according to Wilkes (1979) and TenWolde *et al.* (1988), λ along the grain is 1.5–2.8 times greater than conductivity across the grain, with an average of about 1.8.

Sonderegger *et al.* (2011) reported that λ of Norway spruce and European beech in longitudinal direction was more than twice as high as in both directions perpendicular to grain and clearly higher in radial than in tangential direction. In contrast, Kol (2009) reported that λ of Scots pine wood in radial direction was relatively similar to λ in tangential direction. Such differences might occur due to the influence of volume of ray cell in hardwoods and by the volume of latewood in softwood (Rowley, 1933; Steinhagen, 1977). Sonderegger *et al.* (2011) extended their research to different grain angles perpendicular to grain and found out that the highest λ was between a grain angle of 15 and 75 degree for both investigated species. Whereas the highest λ for spruce was determined in direction of grain, in the case of beech, the highest λ was determined at a grain angle of 15 degree. Authors attributed this phenomenon to the high microfibril angle in the S2 layer of the beech cell walls because the cellulose favours the heat transport along the molecular chain. Recently, Vay *et al.* (2015) derived a theoretical curve from the respective rotation of the λ tensor, which showed excellent agreement with experimental λ data at angles to the grain in the longitudinal radial plane of European oak (*Quercus* sp.), European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*).

5.6.4.4 Temperature

MacLean (1941) was among the first who concluded that the effect of temperature on λ of wood is relatively minor. Steinhagen (1977) indicated that the effect of temperature is about 0.2% per °C. Confirmation of the latter was also published by Glass and Zelinka (2010) who indicated the λ rise of 2%–3% per 10°C. Wilkes (1979) published results of increase of λ of pine wood with MC of 6% from ca. 0.09–0.10 W/m K at a temperature range of about −50°C to 30°C. According to Kanter (1957), the influence of temperature on λ of wood is more prominent at higher wood MCs, especially over the fibre saturation point. Suleiman *et al.* (1999) reported that at temperature increases from 20°C to 100°C, λ of birch wood is increased to 14% in longitudinal and 24% in transverse directions, which is in good agreement with previous reports. However, this effect is contrary to general expectations of air filling the voids in the wood. As the temperature increases, the density of air decreases, which leads to the lower λ through the voids. Higher values of λ at 100°C might therefore be due to another mode of heat transfer, which involves not only simple heat transfer by conduction but also the microstructure of cell wall substance. At the cellular level, the crystalline structure of cellulose chains may be altered due to high temperatures, which could consequently lead to the strength loss and changes in tensor ability to conduct heat.

5.6.4.5 Other wood properties

Besides wood density, MC, orientation and temperature, a number of other factors also influence on λ, such as extractive content, checks, knots, microfibril angle, growth rings, ray cells and porosity (TenWolde *et al.*, 1988; Dupleix *et al.*, 2012). However, there is a lack of literature with results of tests dealing with influences of these wood properties. According to Wenger (1984), λ increases as extractive content of the wood increases. λ of wood is also affected by the orientation of wood cell wall molecules. The orientation of the cellulose microfibrils is supposed to strongly affect λ, with the highest λ along the microfibrils. On the other hand, the middle lamellae and the cell corners, which are rich with lignin, had lower conductivities compared with the S2 layer (Vay *et al.*, 2013). Sonderegger *et al.* (2011) also interpreted their results with the influence of high microfibril angle in the S2 layer of beech wood cell walls as being due to favourable heat transport along cellulose molecular chains. Ray cells are also a pathway for heat transport in radial direction. This is particularly prominent at hardwoods, due to the high amount of ray cells and consequently higher λ in radial direction compared with tangential (Rowley, 1933). Porosity influences λ *via* air and/or water present in lumens and their distribution. Conduction through voids is the dominant factor influencing λ on the microstructure level (Suleiman *et al.*, 1999).

5.6.5 Conclusions

The most important thermal properties of wood are λ, heat capacity and thermal diffusivity, among which λ is most commonly used for calculating insulating properties of various building parts. λ of wood can be measured with several different methods. The most common is HP method, whereas HF, TPS and MTPS, THW, THS and THB

methods can also be used to determine λ. Besides these methods, numerical modelling is a potential approach to analyse λ of wood. Wood properties, which have the most prominent effect on the λ, are wood density, MC, orientation (anisotropy) and temperature, whereas extractive content, checks, knots, microfibril angle, growth rings, ray cells and porosity also influence wood λ. The relation between density, temperature and moisture and λ in the direction of fibres and perpendicular to them is approximately linear. λ increases with the increase of all three properties. λ is affected by wood anisotropy and is dependent on the direction of heat transition. λ in longitudinal direction (parallel to grain) is greater than λ in the transverse direction, and λ in radial direction is generally slightly higher than in tangential. There are also other wood properties, which influences on λ of wood. λ increases with the increase of wood extractives. Microfibril angle in cell walls influences on λ due to favourable heat transport along cellulose molecular chains, whereas ray cells influence especially on λ of hardwoods due to radial orientation and consequently better HF in this direction.

5.7 Fire performance of bio-based building materials

J. Schmid, M. Klippel*, B. Östman†*
*ETH Zurich, Zurich, Switzerland
†Linnaeus University, Växjö, Sweden

5.7.1 An introduction to reaction to fire and resistance to fire

Fire performance is a very general term inaccurately used by industry representatives or researchers whenever important, but complex behaviour of structures exposed to fire is addressed. However, science and standardisation define very accurately the two terms ‘reaction to fire’ and ‘fire resistance’, which are in line with the fundamental physics of a fire. This chapter gives an introduction into the background and usage of these two characteristics and highlights important points for bio-based building products. Further, the authors give guidance for research topics, relevant boundary and test conditions, limitations, related standards and further literature.

Fire safety is an essential requirement of our society. In Europe, the European Union did significant effort to harmonise the general conditions of several characteristics of construction products to ease the flow of products. For all construction products, fire safety is one of the seven essential requirements requested in the construction product regulation (CPR, Official Journal Council Directive 89/106/EEC OJ L 88 of 4 April, 2011), updated version of constructive product directive (*CPD*) from 1988. The CPR requirements on fire safety are that constructions must be designed and built such that in the case of fire:

- load-bearing capacity can be assumed for a specific period of time,
- generation and spread of fire and smoke is limited,
- spread of fire to neighbouring constructions is limited,

– occupants can leave the construction or be rescued by other means,
– safety of rescue teams is taken into consideration.

Fire is an accidental design scenario, which has to be considered as other loading conditions like wind or earthquake. Considering the high number of buildings, fires are very rare, but in case of a fire, the damage of the structure might be disastrous.

Fire safety of buildings is an interaction of (i) products (geometry and buildup), (ii) their materials and (iii) their behaviour in their environment. To cover this interaction and the different needs of a building and to meet given requirements, the behaviour of a construction product can be described by its (a) reaction to fire performance and its (b) fire resistance performance. Whilst the (a) reaction to fire performance is used to describe the behaviour of all construction products, the (b) fire resistance performance is applicable for structural and compartment separating elements.

To compare products with each other, for testing of both the (a) reaction to fire performance and the (b) fire resistance performance, standardised methods with standardised thermal loading conditions have been developed (EN 13501-1, CEN, 2009a; EN 13501-2, CEN, 2009b) despite the fact that in real fires, the actual fire may deviate considerably, depending on the available fire fuel, the ventilation condition, the geometry and the thermal inertia of the compartment. Whilst traditional fire design and many building regulations require standardised fire resistance classification, for example, R60 (see Section 5.7.4), fire safety engineering (*FSE*) assesses project-specific goals and project-specific fire loading to individually design structures. FSE can be defined as the application of scientific and engineering principles to the effect of fire in order to reduce the loss of life and damage to property by quantifying the risks and hazards involved and provide optimal solution to the application of preventive or protective measures (EN ISO 13943, CEN, 2010).

A real fire in a compartment can be divided using the development of the temperature in the fire compartment; see Fig. 5.37. After ignition, severe fires can grow very

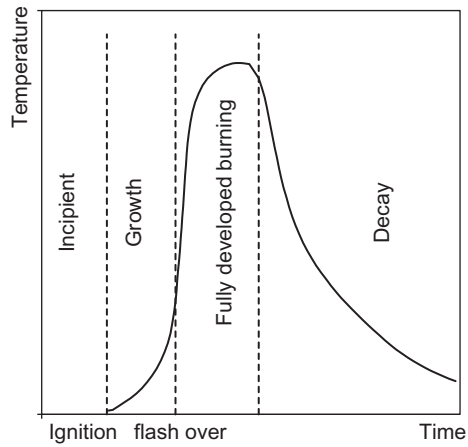


Fig. 5.37 Typical phases of a building fire development. The reaction to fire testing covers the incipient and growth phase, whilst the fire performance of structural member in the fully developed fire is covered by fire resistance tests.

rapidly, but some grow slowly and will stay in the stage of smouldering combustion (flameless combustion) for a whilst until they grow or self-extinguish. The growth of a fire may be counteracted by suppression systems, for example, sprinklers, or the invention of fire services. Uncontrolled, ventilation controlled fires will reach a stage where all oxygen in the compartment is consumed, and further fire development and temperature in the compartment will be governed by the available oxygen inflow, for example, through windows, which normally can resist fire exposure for a very limited time only. The maximum temperature is further governed by the thermal inertia of the compartment surfaces. Whenever the fire load, normally the movable items, is consumed, the fire will pass from the burning phase to a decay (cooling) phase.

Reaction to fire classification is considered to be related to the early phases of a fire before flashover, whilst it is of secondary importance when the fire has reached the fully developed burning phase. In that phase, the fire resistance, that is, the load-bearing capacity and separating function, is decisive to prevent collapse and spread to other parts of the building.

It should be noted that, deviating from reality as indicated in Fig. 5.37, the standard fire temperature-time curve has no decay phase.

As fire safety is a complex term answering a large range of national and regional traditions, a harmonised approach is very difficult to reach. Despite the fact that European countries agreed on many test and design standards, differences are still available as the countries and regions are allowed to define individually general targets, distinct requirements or exceptions. National approaches are often a result of experiences and typical building product applications, which are reflected by building regulations. The national regulations are considered to define the level of safety, but the characteristics are defined by harmonised test standards. In general, standards are the agreement of industry representatives from different companies and countries achieved by consensus. Researchers are often involved in the drafting of a standard. Considering the mentioned procedure, a state of practice (*SOP*) is defined by means of standards and regulations. In contrast, individual approaches, sometimes exceptionally accepted by authorities, are often based on the state of art (*SOA*). Further, very recent approaches may be covered by state of research (*SOR*) where successful applications are missing and further evaluation is needed. Concerning the verification of fire safety of buildings, SOP can be considered as the interaction of European standards and national building regulations. For building products, this SOP approach may be regarded as inflexible and inappropriate for new applications. It should be considered that innovative solutions are difficult to put into the SOP system as it was designed for standard solutions where industry set rules for known applications. Thus, by definition, new approaches have to find their way through the system of SOP or seek alternative ways.

5.7.2 Fire safety of buildings with bio-based products

Fire safety has to be provided by any type of structure, regardless the material and the products are made from. Fire safety of buildings is the interaction of several characteristics. In practice, many terms are used in connection to fire safety of products, which is often mentioned as fire behaviour or fire performance. The reaction to fire

classification can be seen as the quantification of the contribution of a building material to the fire spread and the fire development. In contrast, fire resistance is a nearly independent characteristic for the fire performance of structural elements.

Bio-based building products may be used as, for example, linings, directly in contact with the room environment or within a building construction, for example, as cavity insulation. Load-bearing elements may be unprotected (visible) or initially protected (invisible). In case of fire, their contribution to the fire may be different, but for their classification with respect to reaction to fire, the product is assumed to be exposed directly to fire and tested as such. Very recently, a further characteristic was introduced in Europe to assess the sensitivity of building products to sustained smouldering, which might be of significant relevance for low-density bio-based insulation (EN 16733, CEN, 2015a).

If directly exposed, during the early stage of a fire (pre-ignition, ignition and fire spread) until the flashover, the products in a fire compartment may contribute to the fire growth and interact with other products in the fire compartment. Generally speaking, in this phase, temperatures in the compartment will increase; combustible gases will be produced and may spread to other areas. It is assumed that combustible products will accelerate this process. When flashover is reached, that is, when the combustible gases ignite and almost uniform temperature is reached in the compartment, all materials will interact with the fire regardless their reaction to fire classification. The differences in reaching the flashover can be significant although studies show that the fire load within the room may be more significant than the reaction to fire classification of the wall and ceiling materials; see Fig. 5.38 (Studhalter, 2013).

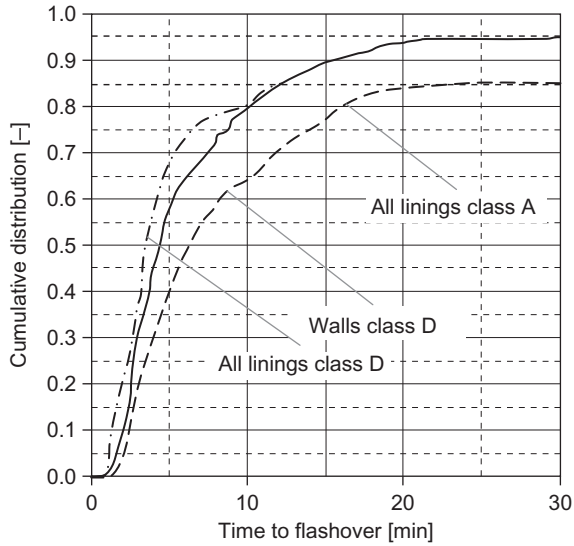


Fig. 5.38 Cumulative distribution of time to flashover in compartments with different surfaces: combustible (European class D) and non-combustible surfaces (class A). Modified from Studhalter (2013).

Today, there are no standardised methodologies on how the contribution of materials with distinct reaction to fire class to fire development and fires spread may be taken into account in FSE approaches. Present approaches include very simple approaches where the charcoal depth of solid wood (e.g. for CLT panels) should be considered as additional fire load and complex models based on finite element analysis are available in computational fire dynamic software codes.

5.7.2.1 *Reaction to fire performance of bio-based building products*

Reaction to fire means the response from materials to an initial fire attack and includes properties like time to ignition, flame spread, heat release rate and smoke production; see Fig. 5.39. These properties are relevant in the early fire development, which is the stage when combustible products may contribute to the fire.

5.7.2.2 *European system for reaction to fire performance*

A European classification system (EN 13501-1, CEN, 2009a) for the reaction to fire properties of building construction products was introduced by a Commission decision in 2000. It is often called the Euroclass system and consists of two subsystems, one for construction products excluding floorings, that is, mainly wall and ceiling surface linings (see Table 5.8), and another similar system for floorings. Both subsystems have classes A–F, of which classes A1 and A2 are non-combustible products. This European system has replaced the earlier national classification systems, which have formed obstacles to trade.

The European classification system for reaction to fire performance is based on a set of EN standards for different test methods. Three test methods are used for determining the classes of combustible building products; see Table 5.9. For non-combustible products, additional fire test methods are used.

The European system must be used for all construction products in order to get the CE mark, which is the official mandatory mark to be used for all construction products on the European market. Different product properties have to be declared and

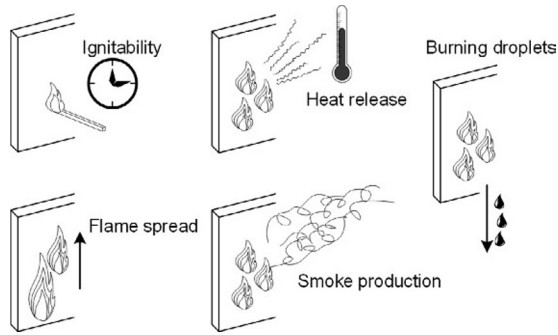


Fig. 5.39 Reaction to fire properties of surface products such as wall and ceiling linings.

Table 5.8 Overview of the European reaction to fire classes for building products excluding floorings

Euro class	Smokeclass	Burning droplet class	Requirements according to			*FIGRA*	Typical products
			Non-comb	*SBI*	Small flame	W/s	
A1	–	–	×	–	–	–	Stone and concrete
A2	s1, s2 or s3	d0, d1 or d2	×	×	–	≤120	Gypsum boards (thin paper) and mineral wool
B	s1, s2 or s3	d0, d1 or d2	–	×	×	≤120	Gypsum boards (thick paper) and fire retardant-treated wood products
C	s1, s2 or s3	d0, d1 or d2	–	×	×	≤250	Coverings on gypsum boards
D	s1, s2 or s3	d0, d1 or d2	–	×	×	≤750	Wood and wood-based panels
E	–	– or d2	–	–	×	–	Some synthetic polymers
F	–	–	–	–	–	–	No performance determined

SBI, single burning item, main test for the reaction to fire classes for building products, EN 13823 (CEN, 2002); FIGRA, fire growth rate, main parameter for the main fire class according to the SBI test.

Table 5.9 European test methods for the reaction to fire classes of combustible building products

Test method	Construction products excluding floorings	Floorings	Main fire properties measured and used for the classification
Small flame test, EN ISO 11925-2 (ISO, 2010a)	×	×	Flame spread within 60 or 20 s
Single burning item test, SBI, EN 13823 (CEN, 2002)	×	–	– FIGRA, fire growth rate – *SMOGRA*, smoke growth rate – Flaming droplets or particles
Radiant panel test, EN ISO 9239-1 (ISO, 2010b)	–	×	– *CHF*, critical heat flux – Smoke production

may vary for different products, but the reaction to fire properties is mandatory for all construction products. The normal route is that each manufacturer tests and declares their own products individually.

5.7.2.3 Reaction to fire performance of wood products

Products with known and stable performance may be classified as groups according to an initiative from the European Commission (CONSTRUCT 01/491). This is a possibility for wood products that have a fairly predictive fire performance. Properties such as density, thickness, joints and type of end-use application may influence the classification. The procedure is called classification without further testing (*CWFT*) and is a list of generic products, not a list of proprietary products.

The CWFT approach has been applied to several types of wood products, for example, WBP – for example, particle board – structural timber, glued laminated timber, solid wood panelling and claddings and wood floorings. Most of the wood products included fall in classes D-s2, d0 or D_{fl}-s1 (for floorings). Data are given in tables consisting of the reaction to fire classification of different wood products and end-use applications. These tables have been approved by the European Commission and published in their official journal. The tables are also included in the relevant harmonised product standards (e.g. EN 13986 (CEN, 2004d), EN 14915 (CEN, 2013c), EN 14342 (CEN, 2013d), EN 14080 (CEN, 2013e) and EN 14081-1 (CEN, 2016d)) and may be used for CE marking.

The main product parameters influencing the reaction to fire characteristics of wood products are thickness, density and mounting including substrate. A simplified version of reaction to fire classes for WBP is given in Table 5.10.

Further details on the CWFT classification are available in the European guideline (Östman *et al.*, 2010) and in the relevant product standards.

Wood products and end-use applications not included in the CWFT classification tables have to be tested and classified in the ordinary way. Better classification may then be reached, since no safety margins have to be fulfilled.

Table 5.10 Classes of reaction-to-fire performance for wood-based panels: Examples

Product	End-use condition	Min. density (kg/m^3)	Min. thick-ness (mm)	Class (excluding floorings)
Fibreboard, hard	Without an air gap behind the wood-based panel	900	6	D-s2 and d0
Wood-based panels	Without an air gap behind the wood-based panel	600	9	D-s2 and d0
Wood-based panels	With a closed or an open-air gap not more than 22 mm behind the wood-based panel	600	9	D-s2 and d2
Wood-based panels	With a closed air gap behind the wood-based panel	600	15	D-s2 and d0
Wood-based panels	With or without an air gap behind the wood-based panel	600	18	D-s2 and d0
Wood-based panels	All	600	3	E
Fibreboard, soft	All	250	9	E

Fire retardant-treated wood products have always to be tested and classified separately; since the treatments may influence their reaction to fire performance, they may then reach the CE mark. Data on reaction to fire performance of other bio-based products than wood are not known or published scientifically.

5.7.3 Fire retardant treatments for wood products

It is relatively easy to obtain an improved fire performance of wood products. Most existing fire retardants are effective in improving different reaction-to-fire parameters of wood such as ignitability, heat release and flame spread. The highest European and national fire classifications for combustible products, i.e. Euroclass B, may be reached (Östman *et al.*, 2001). However, high retention levels have to be used compared with ordinary preservation treatments used to protect wood against biological decay.

Fire retardant treatments for wood are numerous and can be divided into three general types:

- Those incorporated into wood composite products and WBP during manufacture
- Those pressure impregnated into solid wood, plywood, particle board and hardboard industrially, but after manufacture
- Those applied, as paints or surface coatings, industrially after manufacture or in situ after the wood products have been installed in a building

Fire retardants may influence the reaction to fire properties, but for the fully developed fire, the influence is expected be minor (Nussbaum, 1988). One exception is intumescent paints that may delay the time for the start of charring and thus increase the fire resistance of timber structures. In any case, fire retardants cannot make wood non-combustible.

However, the excellent fire performance of the virgin fire retardant, *FR*, wood products may degrade with time, especially in outdoor applications. Thus, when exposed to high humidity, the FR chemicals may migrate in the wood towards the surface and may ultimately be leached out. Even at moderate outdoor humidity and indoors, the fire performance may deteriorate because the FR chemicals migrate away from the surface towards lower concentration regions deeper inside the material, thus increasing flammability of the product.

Interior linings and claddings are probably the main end use of fire retardant-treated wood products. Improved reaction to fire class is required for surface linings in larger and higher buildings in most national building codes, for example, in escape routes, flats in higher residential buildings, public buildings, assembly halls and sport arenas.

Exterior use as, for example, facades may also be possible, and the fire requirements may be fulfilled, but the long-term durability of the reaction to fire properties is difficult to reach; see below. There are also a lot of special applications, for example, exhibitions, packages and transportation on land and sea and off-shore. Mining applications have traditionally been an important end use of fire retardant wood products.

5.7.3.1 *Durability classes for fire performance – principles and methods*

Fire retardants may considerably improve the reaction to fire properties of wood products, but the durability in interior and exterior applications needs to be addressed. Requirements on durability of the fire performance are not mentioned explicitly in most building codes. This is probably partly not only caused by unawareness of the problem but also may be due to the lack of procedures.

The problems with maintained reaction to fire performance over time have been known for a long time in the United States and the United Kingdom but are not so well-known in the rest of Europe. A US study on exterior exposure of North American products for 10 years (LeVan and Holmes, 1986) and a literature review (Östman *et al.*, 2001) have been published.

Two cases of durability of the fire retardant treatment of wood products can be identified. One is the risk for high moisture content and migration of the fire retardant chemicals within the wood product and salt crystallisation on the product surface. These hygroscopic properties of the treated wood-based product can be evaluated by exposure to high relative humidity. The other case is the risk for decreased fire performance due to loss of the fire retardant chemicals by leaching or other mechanisms. This case is mainly for exterior applications, for example, as façade claddings. Maintained fire performance over time has to be verified.

A European system with durability of reaction to fire performance, *DRF*, classes has been developed to guide the potential users to find suitable *FRT* wood products (CEN/TS 15912, CEN, 2012a); see Table 5.11. The system is based on a North

Table 5.11 Requirements for DRF classes of FRT wood products according to CEN/TS 15912 (CEN (2012a))

DRF class	Intended use	Fire class Initial	Performance requirements for different end uses	
			Hygroscopic properties	Fire performance after weather exposure
ST	Short term	Relevant fire class	–	–
	Interior and dry applications	Relevant fire class	Limited moisture content Minimum visible salt	–
	Interior and humid applications	Relevant fire class	Limited moisture content Minimum visible salt	–
	Exterior applications	Relevant fire class	Limited moisture content Minimum visible salt	Maintained fire performance

Further details are given in CEN/TS 15912 (CEN (2012a)).

American system and a previous Nordic system. It consists of a classification system for the properties over time of FRT wood and suitable test procedures.

The technical specification CEN/TS 15912 is currently (2016) being transformed to a full European standard.

5.7.4 *Conclusions on fire retardant treatments for wood products*

Some conclusions on fire retardant treatments of wood products and suggestions for further work have recently been presented (Östman and Tsantaridis, 2016):

- Fire retardant treatments, FRT, may improve the reaction to fire performance of wood products. The highest reaction to fire classification for combustible products may then be reached.
- FRT has limited or no effect on the fire resistance of full building elements, since the charring rate is not changed significantly. One exception is intumescent coatings that may delay the start of charring and thus increase the fire resistance of timer elements.
- However, the excellent fire performance of the virgin FRT wood products may degrade over time, especially in outdoor applications. A system with durability of reaction to fire performance (DRF) classes to evaluate the fire performance of FRT wood products over time at humid and exterior conditions has been developed. It provides a very useful supplement to requirements on the fire performance in national building codes and enables to guide potential users to find suitable and reliable FRT wood products.

- The fire properties of FRT wood products may be maintained after accelerated ageing and natural weathering if the retention levels are high enough, but several FRT wood products lose most of their improved reaction to fire properties during weathering.
- Structural degradation of FRT wood used as roof elements may occur, but it is relevant only for load-bearing uses, which is common in Northern America.
- The main use of FRT wood is as surface linings in interior applications, for example, in escape routes, flats in higher residential buildings, public buildings, assembly halls and sport arenas.
- No studies on the fire performance according to the European system of FRT bio-based products other than wood are known or published scientifically.

Suggestions for further work are the following:

- There is a need to develop new FRT wood products with improved long-term durability of the reaction to fire performance at exterior applications. Industrial objectives are new markets for such wood products, for example, in multi-storey facades.
- The relationship between accelerated and natural weathering in different climates in order to further develop the conditions for accelerated weathering should be studied by international cooperation.
- Cost- and time-effective durability screening tests for FRT wood products should be developed.
- When developing fire retardant treatments for new bio-based products, test procedures with a clear link to the European fire test procedures for building products should be used, for example, the cone calorimeter (ISO, 2002).
- All these aspects have to be combined with requirements for SLPs and an overall ecological performance.

5.7.5 Fire resistance of bio-based building products

Regardless the building material, the fire design of structures using bio-based building products can be performed considering the global structure, part of the structure or single members. The characterisation of the fire behaviour of building products and building assemblies is based on the following criteria:

– Where mechanical resistance is required, structures shall be designed and constructed in such a way that they maintain their load-bearing function during the relevant fire exposure (load-bearing R). This criterion is usually addressed with the duration of time or time of fire resistance for which the member fulfils certain requirements whilst exposed to a certain standardised fire.
– Where fire compartmentation is required, the elements forming the boundaries of the fire compartment, including joints, shall be designed and constructed in such a way that they maintain their separating function during the relevant fire exposure. This shall include, when relevant, ensuring that (1) integrity failure does not occur (integrity E) and/or (2) insulation failure does not occur (insulation I) and/or (3) thermal radiation from the unexposed side is limited (Fig. 5.40).

The certification of the abovementioned requirements can thereby be either achieved by fire tests or using calculations methods if available. The considered fire load to determine the members' fire resistance is usually based on standard fire curves. National rules may request further verifications depending on the product. The standard fire

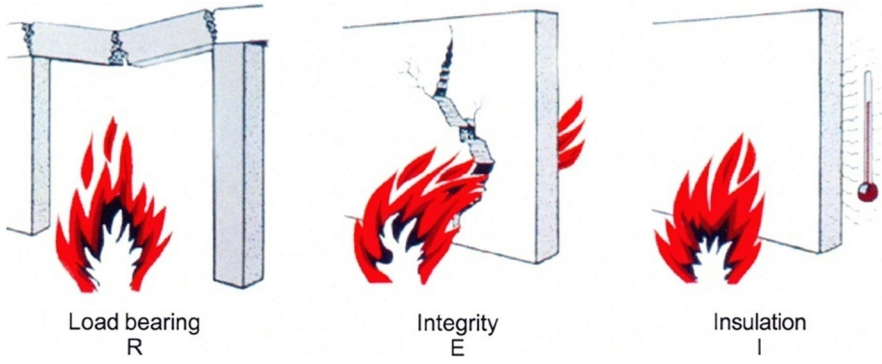


Fig. 5.40 Performance criteria for fire resistance. They are used together with a time value, for example, REI 60 for an element that maintains its load bearing and separating functions in 60 min (Östman *et al.,* 2010).

curve forms the basis for furnace tests on single members in order to classify these members with regard to their fire resistance performance.

5.7.5.1 Separating function

The separating function (requirement on integrity E and insulation I) of wall and floor assemblies from assemblies made from timber can also be determined using calculation methods. A common calculation method is the component additive method to account for a layered construction by adding the contribution to the fire resistance of each layer. The basis of this calculation method has been introduced in the first generation of Eurocode for timber structures (EN 1995-1-2, CEN, 2004c). Later, the calculation method to verify the separating function has been further developed and extended (Frangi *et al.*, 2010) to improve the flexibility of the method and allow the future extension of the calculation rules to consider other products. The improved design method to verify the separating function of wall and floor assemblies is able to consider an unlimited number of layers and an extensive number of (bio-based) materials; see (Östman *et al.*, 2010). However, no European standard is available yet to determine product specific equations to be used in this novel design model. The Fire Safety in Timber Buildings Handbook (Östman *et al.*, 2010) gives information and equations for these main parameters for some (bio-based) materials. Further, different calculation examples are presented in this handbook to verify the separating function of floor and wall assemblies. Using the calculation method, criterion I (insulation) is verified. Criterion E (integrity) is assumed to be fulfilled as long as criterion I is fulfilled, and general construction rules (e.g. supported joints) are followed. The method is limited to timber assemblies (frame made from wood) as deformation in case of a fire is very limited in contrast to assemblies made of metal elements. Deformations of steel studs may lead to significant cracking in the lining layers, and the abovementioned assumption would not be valid.

The component additive method for verification of the separating function uses the following assumptions:

- The assembly is exposed to standard fire temperature-time curve.
- The fire protection of each layer is defined as the time until loss of the fire-protective function and is reached when the average temperature over the whole unexposed surface exceeds 250°C or when the maximum temperature at any point of that surface exceeds 270°C.
- The basic insulation time is defined as the fire resistance of a single layer without the influence of adjacent materials and is reached when an average increase of the temperature by 140°C is reached or when a maximum temperature rise at any point exceeds 180°C on its unexposed surface.

These temperature criteria build the basis of the equations to determine the basic insulation values and protection values for a number of bio-based building products as given in the Fire Safety in Timber Buildings Handbook (Östman *et al.*, 2010).

In this context, a further temperature criterion should be mentioned. The start of charring of timber surfaces protected by fire-protective claddings made of bio-based products and gypsum plasterboards is assumed at a temperature of 300°C (EN 1995-1-2, CEN, 2004c).

The start of charring normally occurs when fire exposure starts, which is at the flash-over point in compartment fires or at the beginning of a standard fire test in a furnace. Whenever a bio-based material, for example, a timber member, is initially protected by a fire protection system, for example, a lining of gypsum plasterboards, the start of charring is delayed. This time can be determined by a test according to EN 13381-7 (currently in revision, 2016), which estimates the ability of a protection system to delay the start of charring and reduces the charring rate subsequently.

To determine the parameters for different bio-based building products for the use of the calculation model, fire resistance tests using standard fire according to ISO 834-1 (ISO, 1999) need to be performed.

To provide guidance about the inclusion of new materials in the method, a joint research project between Eidgenössische Technische Hochschule Zürich (ETH), Technical University Tallinn (TUT), Technical University Munich (TUM) and Technical Research Institute of Sweden (SP HSt) has started. This project aims to develop a procedure to develop specific product-fitted equations that are needed to verify the separating function of wall and floor constructions with the current method. The procedure will give clear guidance on how to perform fire tests, evaluate these tests and subsequently perform finite element (*FE*) analysis to determine temperature-related material properties (e.g. specific heat and conductivity) and finally the input values for the method (protection time and position coefficients).

5.7.6 Load-bearing function

Besides the separating function, the load-bearing performance of structural elements is covered by the term ‘fire resistance’. The fire resistance classification for load-bearing assemblies or members uses the abbreviation ‘R’ combined with a number symbolising the minutes of fire resistance under standard fire exposure. Usually, steps of 15 or 30 min are used; see Fig. 5.40. It should be considered that the time of fire resistance of load-bearing elements is strongly related to the applied load. In general, failure of

fire-exposed members occurs earlier, the higher the load and thus the closer the applied load to the maximum load-bearing capacity of a member at normal temperature. This means that the fire resistance of, for example, a load-bearing glulam beam of a certain dimension may be R60 or R30 depending on the applied load.

Until today, only wood and EWP can be considered as load-bearing members in a structural design, but no other bio-based products exist. Whilst some wood-based products, for example, plywood, oriented strand boards, OSB and medium fibreboards, have a verified load-bearing capacity at normal temperature, only limited knowledge about their structural performance in fire is available. However, they have been proved to fulfill the requirements for fire protection ability of, for example, load-bearing members according to EN 14135 (CEN, 2005d) (Östman and Boström, 2015). These wood-based products are usually plane boards and thus no linear (e.g. beam) structural members of wood-based products exist at the moment. It should be noted that the performance of the adhesive at elevated temperatures may be crucial for the structural performance of some members, but it is not a characteristic in insulation.

The essential verification of the load-bearing capacity can be done by means of calculations, tests or a combination of both. In Europe, the design follows Eurocode design methods, whereby part five is the design standard for structural timber. Based on the design code for normal temperature, part 5-1-1, the fire design shall be done in accordance to part 5-1-2 (EN 1990 (CEN, 2012c); EN 1995-1-1 (CEN, 2004a) and EN 1995-1-2 (CEN, 2004c)). Eurocode and other available design standards use the charring rate as the main parameter to determine the load-bearing capacity after a distinct time of fire exposure. Thereby, the charring rate is defined as the rate (depth per time) at which wood is fully converted to charcoal, whilst other codes, for example, in Japan, use an increased, so-called effective, charring rate to consider losses of strength and stiffness of the heated residual cross-section (virgin wood). Eurocode uses a two-step procedure. In the first step, (i) charring rates determined from innumerable fire resistance tests (Frangi and Fontana, 2003) are used to calculate a residual cross-section geometry; in the second step, (ii) an effective cross-section is calculated to consider the losses in strength and stiffness of the heated material beyond the char layer.

On the one hand, the development of the char layer is the reason for the loss of the cross-section, but at the other hand, it represents a heat barrier against the heat in the fire compartment. Due to the porous structure, char has a low mean density and can be considered as an insulating layer protecting the remaining cross-section. A char layer of 25 mm is considered as a 'fully developed' layer to provide significant fire protection. During the early stage of a fire, the increase in thickness can be seen as the reason why the charring rate in a standard fire is linear although the temperature increase is exponential. The loss of char layer thickness would lead to a faster charring of the remaining cross-section (Schmid *et al.,* 2016). Wood modification may improve the fire resistance of members although the improvement of the reaction to fire classification is often the main effect of wood modification. Theoretically, a decreased char temperature, that is, the temperature where wood is converted to char, may be favourable as the insulating layer would be built up earlier. However, when the process does not stop, advantages may be abrogated.

The calculation rules given in Eurocode 5 predict the load-bearing capacity of timber members in a fire resistance test. Whilst in a fire resistance test, failure of the

specimen and criteria for the deflection and the deflection rate are used to terminate a test, the design of the fire resistance does not consider requirements for the deflection of elements as service limit state (*SLS*) requirements are usually not requested in fire. However, it should be considered that large deformations may lead to a change of the mechanical system and thus may affect the ultimate limit state (*ULS*), which has to be verified in the fire situation.

5.7.6.1 Testing of fire resistance of load-bearing elements

Due to the high degree of complexity of the behaviour of materials and products in the fire situation, the use of many building products is based on testing. For load-bearing elements, several fire resistance test results are available depending on the product. Fire resistance tests exist for walls, floors and roofs, beams, columns, balconies and walkways and stairs.

As many companies often aim for a certain classification of their products, fire resistance tests are performed with a specified load, for example, 20 kN/m, and terminated after the predefined goal, for example, 30 min, is reached. From a scientific point of view, these results are not sufficient to describe the performance of a product as (i) continuation of the test may lead to failure (collapse) one moment later or after a significant time. The same uncertainty can be stated for the load. (ii) Insignificant increase of the load may lead to failure before the required 30 min fire resistance is reached. Therefore, it is always recommended to perform a fire resistance test until failure (e.g. structural failure due to collapse or significant deflection rate or integrity) is reached to gain the most possible information from the test.

Independent from the material of a member, for a scientific exploitation of fire resistance test results, the knowledge about the (i) exact time of failure of the specimen is essential. Further (ii), the applied load has to be in a well-defined relationship to the load-bearing capacity of the element at normal temperature. For wood-(based) products, it is further (iii) needed to know the residual cross-section at the failure time to determine the parameters for calculation models in general and the losses in strength and stiffness due to the heated, uncharred residual cross-section (Schmid *et al.*, 2015). It should be considered that for the development of product-tailored calculation rules, several fire resistance test results have to be evaluated. As large-scale fire tests are very costly, model-scale tests might be appropriate for parametric studies where the influence of single parameters only is evaluated.

It should be noted that fire resistance tests for specific solutions are very likely to provide more optimistic results than calculations, which have to provide a safety margin. Reasons for this are the scatter of the material properties (e.g. strength of timber) and the safety philosophy behind calculation models, which have to lead to non-conservative (safe) results and testing where it is accepted to replace unfavourable results after successful retesting.

The validity of bench tests, for example, cone-calorimeter tests (ISO 5660-1, ISO, 2002), for the prediction of charring may be used, but the heat exposure is very limited in comparison with standard fire testing. Whilst standard tests with cone heaters are usually made with a constant incident heat flux to the specimens of 35 or 50 kW/m^2 surface, in standard fire resistance tests, corresponding values reach to

180 kW/m^2 at 90 min (Babrauskas, 2005). Further, it should be highlighted that charring influences not only the load-bearing capacity of a timber member but also the heating of the residual, uncharred cross-section, which has to be taken into account accordingly (Schmid *et al.*, 2012).

5.7.6.2 Simulation of fire resistance

Fire testing of the fire resistance performance of building elements is costly, is time-consuming, and is in general restricted to the product details as tested. Simulations are regarded as a cost-efficient way to predict the performance of building elements in general and timber members in specific. Finite element analysis (FEA) is used to perform simulations. Not only several commercial codes exist, but also freeware software is available. Regardless of the simulation approach, to successfully perform simulations, material properties as a function of their temperature are essential.

Whilst thermal properties are needed to perform simulations of the separating function (criterion I) of building products or assemblies and to perform simulations of the load-bearing function (criterion R), the latter need further data with respect to their mechanical response to increased temperature. In general, a complete data set of material properties range from normal temperature, that is, 20°C, to the maximum temperature in the fire situation, between 800°C and 1000°C. Direct testing of the material properties is often not possible (König, 2000). Thermal properties (density, heat conductivity and heat capacity) can be determined based on temperature recording during a fire resistance test. It should be noted that usually effective thermal properties are determined indirectly taking into account several effects (cracks, fissures in charred timber and moisture change). The need of the material properties as a function of their temperature is the reason why the range of materials that can be considered in simulations is limited to timber only, not to other bio-based products, at the moment.

References

Abuku, M., Blocken, B., Roels, S., 2009. Moisture response of building facades to wind-driven rain: field measurements compared with numerical simulations. J. Wind Eng. Ind. Aerodyn. 97, 197–207.

Ammer, U., 1963. Untersuchungen über das Wachstum von Rotstreifepilzen in Abhängigkeit von der Holzfeuchtigkeit. Forstwiss. Centralbl. 82, 360–391.

Anthony, P.A., 1999. The macrofungi and decay of roofs thatched with water reed, *Phragmites australis*. Mycol. Res. 103, 1346–1352.

Arfvidsson, J., 1998. Moisture Transport in Porous Media. Modelling Based on Kirchhoff Potentials (Doctoral Thesis). Lund University, Division of Building Physics, Lund.

AS, 2005. AS 5604:2005. Timber – Natural Durability Ratings.

Asako, Y., Kamikoga, H., Nishimura, H., Yamaguchi, Y., 2002. Effective thermal conductivity of compressed woods. Int. J. Heat Mass Transf. 45, 2243–2253.

Augusta, U., Rapp, A.O., 2003. The Natural Durability of Wood in Different Use Classes, IRG/WP/03-10457. The International Research Group on Wood Protection, Stockholm. p. 15.

Babrauskas, V., 2005. Charring rate of wood as a tool for fire investigations. Fire Saf. J. 40, 528–554.
Barreira, E., de Freitas, V.P., 2013. Experimental study of the hygrothermal behaviour of external thermal insulation composite systems (ETICS). Build. Environ. 63, 31–39.
Bellmann, H., 1988a. Zur Frage der Bewertung von Labor-Versuchsergebnissen über Basidiomyceten-Resistenz der Holzarten. Holz Roh Werkst. 46, 259–267. 289–294.
Bellmann, H., 1988b. Relative resistenz der holzarten gegenüber basidiomyceten. Holz Roh Werkst. 46, 417–425.
Böhner, G., Wagner, L., Säcker, M., 1993. Elektrische Messung hoher Holzfeuchten bei Fichte. Holz Roh Werkst. 51, 163–166.
Boothby, T.E., Burroughs, C.B., Bernecker, C.A., Manbeck, H.B., Ritter, M.A., Grgurevich, S., Courtney, B., Cegelka, P., Hillbrich Lee, D., 2001. Design of Wood Highway Sound Barriers. Research Paper FPL-RP-596, United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.
Bornemann, T., Brischke, C., Alfredsen, G., 2014. Decay of wooden commodities – moisture risk analysis, service life prediction and performance assessments in the field. Wood Mater. Sci. Eng. 9, 144–155.
Brischke, C., Kaudewitz, P., 2015. Acceptance Levels of Surface Disfigurement – Tolerance to Defects of Coated Wood, IRG/WP/15-20564. The International Research Group on Wood Protection, Stockholm.
Brischke, C., Rapp, A.O., 2010. Service Life Prediction of Wooden Components – Part 1: Determination of Dose Response Functions for Above Ground Decay, IRG/WP/10-20439. The International Research Group on Wood Protection, Stockholm.
Brischke, C., Rapp, A.O., Bayerbach, R., Morsing, N., Fynholm, P., Welzbacher, C.R., 2008. Monitoring the "material climate" of wood to predict the potential for decay: results from in situ measurements on buildings. Build. Environ. 43, 1575–1582.
Brischke, C., Welzbacher, C.R., Boeckmann, O., 2011. Critical heat flux densities of various flooring materials for outdoor applications. Eur. J. Wood Wood Prod. 70, 199–207.
Brischke, C., Iseler, N., Meyer, L., Sawyer, G., 2014a. Testing the mechanical resistance of timber used for construction in the marine environment. Int. Wood Prod. J. 5, 39–49.
Brischke, C., Meyer, L., Hesse, C., Van Acker, J., De Windt, I., Conti, E., Humar, M., Viitanen, H., Kutnik, M., Malassenet, L., 2014b. Moisture Dynamics of Wood and Wood-Based Products – Results from an Inter-Laboratory Test, IRG/WP/14-20539. The International Research Group on Wood Protection, Stockholm.
Brischke, C., Alfredsen, G., Flæte, P.-O., Humar, M., Isaksson, T., Meyer, L., 2015. The Combined Effect of Wetting Ability and Durability on Field Performance – Verification of a New Prediction Approach, IRG/WP/15-20565. The International Research Group on Wood Protection, Stockholm.
Brischke, C., Bornemann, T., Rapp, A.O., 2016. Monitoring of a cold roof thatched with reed (*Phragmites australis*) using wooden substitute sensors for moisture content measurements. Restor. Build. Monum. (Accepted for publication).
Buck, W., Rudtsch, S., 2006. Thermal properties. In: Czichos, H., Saito, T., Smith, L. (Eds.), Springer Handbook of Materials Measurement Methods. Springer, Berlin, Heidelberg, pp. 399–429.
Carbon, C.C., Jakesch, M., 2012. A model for haptic aesthetic processing and its implications for design. Proc. IEEE 101 (9), 2123–2133.
Carey, J., 1975. Notes on the Isolation and Characterisation of Wood-Inhabiting Fungi. Building Research Establishment Current Paper CP 93/75, 11 p.
Carey, J., Purslow, D.F., Savory, J.G., 1981. Proposed Method for Out-of-Ground Contact Trials of Exterior Joinery Protection Systems, IRG/WP 2157. International Research Group on Wood Protection, Stockholm. 15 p.

Carslaw, H.S., Jaeger, J.C., 1959. Conduction of Heat in Solids. Oxford University Press, Oxford, England, UK.

Cartwright, K., Findlay, W., 1958. Decay of Timber and Its Prevention, second ed. HMSO, London. pp. 266–288.

CEN, 1992a. EN 20-1:1992. Wood Preservatives – Determination of the Protective Effectiveness Against *Lyctus brunneus* (Stephens) – Part 1: Application by Surface Treatment (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 1992b. EN 275:1992. Wood Preservatives – Determination of the Protective Effectiveness Against Marine Borers. European Committee for Standardization, Brussels, Belgium.

CEN, 1993. EN 314-2:1993. Plywood. Bonding Quality. Requirements. European Committee for Standardization, Brussels, Belgium.

CEN, 1994a. EN 350-1:1994. Durability of Wood and Wood-Based Products – Natural Durability of Solid Wood – Part 1: Guide to the Principles of Testing and Classification of the Natural Durability of Wood. European Committee for Standardization, Brussels, Belgium.

CEN, 1994b. EN 350-2:1994. Durability of Wood and Wood-Based Products – Natural Durability of Solid Wood – Part 2: Guide to Natural Durability and Treatability of Selected Wood Species of Importance in Europe. European Committee for Standardization, Brussels, Belgium.

CEN, 1994c. EN 460:1994. Durability of Wood and Wood-Based Products – Natural Durability of Solid Wood – Guide to the Durability Requirements for Wood to be Used in Hazard Classes.

CEN, 1996. EN 113:1996. Wood Preservatives – Test Method for Determining the Protective Effectiveness Against Wood Destroying Basidiomycetes – Determination of the Toxic Values. European Committee for Standardization, Brussels, Belgium.

CEN, 1997. EN 84:1997. Wood Preservatives – Accelerated Ageing of Treated Wood Prior to Biological Testing – Leaching Procedure. European Committee for Standardization, Brussels, Belgium.

CEN, 1999. EN 1946-2:1999. Thermal Performance of Building Products and Components. Specific Criteria for the Assessment of Laboratories Measuring Heat Transfer Properties. Measurements by Guarded Hot Plate Method, 36 p. European Committee for Standardization, Brussels, Belgium.

CEN, 2001. EN 12667:2001. Thermal Performance of Building Materials and Products. Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods. Products of High and Medium Thermal Resistance, 58 p. European Committee for Standardization, Brussels, Belgium.

CEN, 2002. EN 13823:2002. Reaction to Fire Tests for Building Products. Building Products Excluding Floorings Exposed to the Thermal Attack by a Single Burning Item. European Committee for Standardization, Brussels, Belgium.

CEN, 2004a. EN 1995-1-1:2004a. Eurocode 5: Design of Timber Structures – Part 1-1: General – Common Rules and Rules for Buildings (Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC).

CEN, 2004b. EN 1995-1-1:2004b. Eurocode 5. Design of Timber Structures – Part 1-1 – General – Common Rules and Rules for Buildings. European Committee for Standardization, Brussels, Belgium.

CEN, 2004c. EN 1995-1-2:2004. Eurocode 5. Design of Timber Structures – Part 1-2: General – Structural Fire Design. European Committee for Standardization, Brussels, Belgium.

CEN, 2004d. EN 13986:2004. Wood-Based Panels for Use in Construction – Characteristics, Evaluation of Conformity and Marking. European Committee for Standardization, Brussels, Belgium.

CEN, 2005a. CEN/TS 15083-1:2005. Durability of Wood and Wood-Based Products – Determination of the Natural Durability of Solid Wood Against Wood-Destroying Fungi, Test Methods – Part 1: Basidiomycetes. European Committee for Standardization, Brussels, Belgium.

CEN, 2005b. CEN/TS 15083-2:2005. Durability of Wood and Wood-Based Products – Determination of the Natural Durability of Solid Wood Against Wood-Destroying Fungi, Test Methods – Part 2: Soft Rotting Micro-Fungi. European Committee for Standardization, Brussels, Belgium.

CEN, 2005c. EN 1001-2:2005. Durability of Wood and Wood Based Products – Terminology – Part 2: Vocabulary. European Committee for Standardization, Brussels, Belgium.

CEN, 2005d. EN 14135:2005. Coverings – Determination of Fire Protection Ability. European Committee for Standardization, Brussels, Belgium.

CEN, 2005e. EN 993-15:2005-07. Methods of Test for Dense Shaped Refractory Products – Part 15: Determination of Thermal Conductivity by the Hot-Wire (Parallel) Method, 20 p. European Committee for Standardization, Brussels, Belgium.

CEN, 2009a. EN 13501-1:2009. Fire Classification of Construction Products and Building Elements – Part 1: Classification Using Test Data from Reaction-to-Fire Tests. European Committee for Standardization, Brussels, Belgium.

CEN, 2009b. EN 13501-2:2009. Fire Classification of Construction Products and Building Elements – Part 2: Classification Using Data from Fire Resistance Tests, Excluding Ventilation Services. European Committee for Standardization, Brussels, Belgium.

CEN, 2010. EN ISO 13943:2010. Fire Safety: Vocabulary. European Committee for Standardization, Brussels, Belgium.

CEN, 2012a. CEN/TS 15912:2012. Durability of Reaction to Fire Performance of FRT Wood-Based Products in Interior and Exterior End-Use Applications. European Technical Specification. European Committee for Standardization, Brussels, Belgium.

CEN, 2012b. EN 117:2012. Wood Preservatives – Determination of Toxic Values Against Reticulitermes Species (European Termites) (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2012c. EN 1990:2012. Eurocode – Basis of Structural Design. European Committee for Standardization, Brussels, Belgium.

CEN, 2013a. EN 335:2013. Durability of Wood and Wood-Based Products – Use Classes: Definitions, Application to Solid Wood and Wood-Based Products. European Committee for Standardization, Brussels, Belgium.

CEN, 2013b. EN 599-1:2009+A1:2013. Durability of Wood and Wood-Based Products – Efficacy of Preventive Wood Preservatives as Determined by Biological Tests – Part 1: Specification According to Use Class. European Committee for Standardization, Brussels, Belgium.

CEN, 2013c. EN 14915:2013. Solid Wood Panelling and Cladding – Characteristics, Evaluation of Conformity and Marking. European Committee for Standardization, Brussels, Belgium.

CEN, 2013d. EN 14342:2013. Wood Flooring and Parquet. Characteristics, Evaluation of Conformity and Marking. European Committee for Standardization, Brussels, Belgium.

CEN, 2013e. EN 14080:2013. Timber Structures – Glued Laminated Timber and Glued Solid Timber – Requirements. European Committee for Standardization, Brussels, Belgium.

CEN, 2014a. EN 252:2014. Field Test Method for Determining the Relative Protective Effectiveness of a Wood Preservative in Ground Contact. European Committee for Standardization, Brussels, Belgium.

CEN, 2014b. EN 330:2014. Wood Preservatives – Determination of the Relative Protective Effectiveness of a Wood Preservative for Use Under a Coating and Exposed Out-of-Ground Contact – Field Test: L-Joint Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2014c. EN 73:2014. Wood Preservatives – Accelerated Ageing of Treated Wood Prior to Biological Testing – Evaporative Ageing Procedure. European Committee for Standardization, Brussels, Belgium.

CEN, 2014d. EN 839:2014. Wood Preservatives – Determination of the Protective Effectiveness Against Wood Destroying Basidiomycetes – Application by Surface Treatment. European Committee for Standardization, Brussels, Belgium.

CEN, 2015a. EN 16733:2015. Reaction to Fire Tests for Building Products – Determination of a Building Product's Propensity to Undergo Continuous Smouldering. European Committee for Standardization, Brussels, Belgium.

CEN, 2015b. EN 330:2015. Wood Preservatives – Determination of the Relative Protective Effectiveness of a Wood Preservative for Use Under a Coating and Exposed Out-of-Ground Contact – Field Test: L-Joint Method.European Committee for Standardization, Brussels, Belgium.

CEN, 2016a. EN 350:2016. Durability of Wood and Wood-Based Products. Testing and Classification of the Durability to Biological Agents of Wood and Wood-Based Materials. European Committee for Standardization, Brussels, Belgium.

CEN, 2016b. EN 46-1:2016. Wood Preservatives – Determination of the Preventive Action Against Recently Hatched Larvae of *Hylotrupes bajulus* (Linnaeus) – Part 1: Application by Surface Treatment (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2016c. EN 49-1:2016. Wood Preservatives – Determination of the Protective Effectiveness Against *Anobium punctatum* (De Geer) by Egg-Laying and Larval Survival – Part 1: Application by Surface Treatment (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2016d. EN 14081-1:2016. Timber structures. Strength graded structural timber with rectangular cross section. General requirements. European Committee for Standardization, Brussels, Belgium.

CONSTRUCT 01/491 Rev 3, 2004. Classification of Products of Known and Stable Performance – Procedural Aspects.

Cousins, W.J., 1978. Young's modulus of hemicellulose as related to moisture content. Wood Sci. Technol. 12, 161–167.

CPR, 2011. Construction Products Regulation: Official Journal Council Directive 89/106/EEC OJ L 88 of 4 April, 2011. European Commission, Brussels.

Curling, S., Ormondroyd, G.A., 2016. Moisture sorption of wool insulation materials: comparison of material and product testing approaches. In: COST FP 1303, Hygrothermal Performance of Buildings and Their Materials, Poznan.

Curling, S.F., Stefanoswski, B.K., Mansour, E., Ormodroyd, G.A., 2015. Applicability of Wood Durability Testing Methods to Bio-Based Building Materials, IRG/WP/15-20561. International Research Group on Wood Protection, Stockholm. 12 p.

da Silva, W.P., da Silva, L.D., de Oliveira Farias, V.S., da Silva e Silva, C.M.D.P., de Ataíde, J.S.P., 2013. Three-dimensional numerical analysis of water transfer in wood: determination of an expression for the effective mass diffusivity. Wood Sci. Technol. 47 (5), 897–912.

Damfeu, J.C., Meukam, P., Jannot, Y., 2016. Modeling and measuring of the thermal properties of insulating vegetable fibers by the asymmetrical hot plate method and the radial flux method: kapok, coconut, groundnut shell fiber and rattan. Thermochim. Acta 630, 64–77.

De Groot, R.C., Highley, T.L., 1995. Forest Products Laboratory Methodology for Monitoring Decay in Wood Exposed Above Ground, IRG/WP/95-20074. International Research Group on Wood Protection, Stockholm.

De Smet, J., Van Acker, J., 2006. Testing methodology and CE-marking for biological performance of plywood for exterior construction purposes. In: COST Action E44/E49 Conference on Wood Resources and Panel Properties, Valencia, Spain.

De Windt, I., Van den Bulcke, J., Welzbacher, C.R., Gellerich, A., Bollmus, S., Humar, M., Plaschkies, K., Scheiding, W., Alfredsen, G., Van Acker, J., 2013. Statistical Analysis of Durability Tests – Part 1: Principles of Distribution Fitting and Application on Laboratory Tests, IRG/WP/13-20504. International Research Group on Wood Protection, Stockholm. 12 p.

Defoirdt, N., Gardin, S., Van den Bulcke, J., Van Acker, J., 2009. Moisture dynamics of WPC and the impact of fungal testing. Int. Biodeterior. Biodegrad. 64 (1), 65–72.

Dhakal, H.N., Zhang, Z.Y., Richardson, M.O.W., 2007. Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites. Compos. Sci. Technol. 67, 1674–1683.

DIN, 2011. DIN 68800-1: 2011. Holzschutz – Teil 1: Allgemeines.

Dündar, T., Kurt, S., As, N., Uysal, B., 2012. Nondestructive evaluation of wood strength using thermal conductivity. BioResources 7 (3), 3306–3316.

Dupleix, A., Kusiak, A., Hughes, M., Rossi, F., 2012. Measuring the thermal properties of green wood by the transient plane source (TPS) technique. Holzforschung 67 (4), 437–445.

Edlund, M.L., Nilsson, T., 1998. Testing the durability of wood. Mater. Struct. 31, 641–647.

Engelund, E.T., Thygesen, L.G., Svensson, S., Hill, C.A., 2013. A critical discussion of the physics of wood–water interactions. Wood Sci. Technol. 47, 141–161.

Englund, F., 2013. European Users Expectations for Wood Product Service Life, Deliverable D5.2, PerformWood – Performance Standards for Wood in Construction – Delivering Customer Service Life Needs. SP Technical Research Institute of Sweden, Stockholm, Sweden.

ENV, 2001. ENV 807: 2001. Wood Preservatives – Determination of the Effectiveness Against Soft Rotting Micro-Fungi and Other Soil Inhabiting Micro-Organisms.

ENV, 2002. ENV 12038: 2002. Durability of Wood and Wood-Based Products – Wood-Based Panels – Method of Test for Determining the Resistance Against Wood-Destroying Basidiomycetes.

Evans, F., Flæte, P.O., Alfredsen, G., 2008. Natural Durability of Different Wood Species in Above Ground Applications – Weight and MOE Loss, IRG/WP/08-10667. International Research Group on Wood Protection, Stockholm. 14 p.

Fabiyi, J.S., McDonald, A.G., Wolcott, M.P., Griffiths, P.R., 2008. Wood plastic composites weathering: visual appearance and chemical changes. Polym. Degrad. Stab. 93, 1405–1414.

Fang, Z., Liu, B., Du, G., Chen, J., 2013. Biochemical characterization of three keratinolytic enzymes from *Stenotrophomonas maltophilia* BBE11-1 for biodegrading keratin wastes. Int. Biodeterior. Biodegrad. 82, 166–172.

Filippovych, K., Huinink, H., van der Ven, L., Adan, O.C., 2015. Self Healing Biofilms for Wood Protection. Self Healing Materials: Pioneering Research, The Netherlands. pp. 181–186.

Findlay, W., 1985. Preservation of Timber in the Tropics. Springer, Netherlands. ISBN: 90-247-3112-7237.

Fortino, S., Genoese, A., Genoese, A., Nunes, L., Palma, P., 2013. Numerical modelling of the hygro-thermal response of timber bridges during their service life: a monitoring case-study. Constr. Build. Mater. 47, 1225–1234.

Franco, A., 2007. An apparatus for the routine measurement of thermal conductivity of materials for building application based on a transient hot-wire method. Appl. Therm. Eng. 27, 2495–2504.

Frangi, A., Fontana, M., 2003. Charring rates and temperature profiles of wood sections. Fire Mater. 27, 91–102.

Frangi, A., Schleifer, V., Fontana, M., 2010. Design model for the verification of the separating function of light timber frame assemblies. Eng. Struct. 32 (4), 1184–1195.

Gaylarde, C.C., Morton, L.G., 1999. Deteriogenic biofilms on buildings and their control: a review. Biofouling 14, 59–74.

Gerhards, C.C., 1982. Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects. Wood Fiber Sci. 14, 4–36.

Glass, S.V., TenWolde, A., 2007. Review of In-Service Moisture and Temperature Conditions in Wood-Frame Buildings. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Glass, S.M., Zelinka, S.L., 2010. Moisture relations and physical properties of wood. Wood Handbook—Wood as an Engineering Material, Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, pp. 4-1–4-19.

Gobakken, L.R., Mattsson, J., Alfredsen, G., 2008. In-Service Performance of Wood Depends Upon the Critical In-Situ Conditions, IRG/WP/08-20382. International Research Group on Wood Protection, Stockholm (Case Studies).

Greef, J.M., 2015. The water absorption of reed for roofing depends on the lignin content of the culms. In: COST Action FP 1303 Workshop, March 04–05th, Tallinn.

Green, D.W., Winandy, J.E., Kretschmann, D.E., 2010. Mechanical properties of wood. Wood Handbook: Wood as an Engineering Material, USDA Forest Service, Forest Products Laboratory, Madison, WI, pp. 4.1–4.45 (General Technical Report FPL; GTR-113).

Grote, V., 2012. Stone Pine. Positive Health Effects of Stone Pine Furniture. http://humanresearch.at/newwebcontent/?page_id=96&lang=en.

Gustafsson, S.E., 1987. Transient hot strip techniques for measuring thermal conductivity and thermal diffusivity. Rigaku J. 4 (1–2), 16–28.

Hansson, S.O., 2005. Aesthetic functionalism. Contemp. Aesthet. 3, (online publication).

Hapukotuwa, N.K., Grace, J.K., 2011. Comparative study of the resistance of six Hawaii-grown bamboo species to attack by subterranean termites *Coptotermes formosanus* siraki and *Coptotermes gestri* (wassmann) (blattodea: rhinotermitidae). Insect 2, 475–485.

Highley, T.L., 1995. Comparative durability of untreated wood in use above ground. Int. Biodeterior. Biodegrad. 35, 409–419.

Hovde, P.J., 2002. The factor method for service life prediction from theoretical evaluation to practical implementation. In: Proceedings of 9DBMC International Conference on Durability of Building Materials and Components 17–20, March, Brisbane, Australia.

Hrčka, R., Kurjatko, S., 2006. Thermal properties of elm wood (*Ulmus scabra* Mill.). In: Kurjatko, S., Kudela, J., Lagana, R. (Eds.), Wood Structure and Properties '06. Arbora Publishers, Zvolen, pp. 245–249.

Huckfeldt, T., Schmidt, O., 2006. Hausfäule- und Bauholzpilze – Diagnose und Sanierung. Rudolf Müller, Cologne.

Humar, M., Kržišnik, D., Brischke, C., 2015. The Effect of Preservative Treatment on Mechanical Strength and Structural Integrity of Wood, IRG/WP/15-30667. The International Research Group on Wood Protection, Stockholm, Sweden.

Humphrey, C.J., 1916. Laboratory tests on the durability of American woods - I. Flask tests on conifers. Mycologia 8 (2), 80–92.

Isaksson, T., Thelandersson, S., 2013. Experimental investigation on the effect of detail design on wood moisture content in outdoor above ground applications. Build. Environ. 59, 239–249.

Isaksson, T., Thelandersson, S., Ekstrand-Tobin, A., Johansson, P., 2010. Critical conditions for onset of mould growth under varying climate conditions. Build. Environ. 45, 1712–1721.

Isaksson, T., Brischke, C., Thelandersson, S., 2013. Development of decay performance models for outdoor timber structures. Mater. Struct. 46, 1209–1225.

ISO, 1991. ISO 8302:1991. Thermal Insulation – Determination of Steady-State Thermal Resistance and Related Properties – Guarded Hot Plate Apparatus. International Organization for Standardization, Geneva, Switzerland, 47 p.

ISO, 1999. ISO 834-1:1999. Fire-Resistance Tests – Elements of Building Construction – Part 1: General Requirements. International Organization for Standardization, Geneva, Switzerland.

ISO, 2000. ISO 15686 Part 1:2000. Buildings and Constructed Assets – Service Life Planning – Part 1: General Principles. International Organization for Standardization, Geneva, Switzerland.
ISO, 2002. ISO 5660:2002. Reaction-to-Fire Tests – Heat Release, Smoke Production and Mass Loss Rate – Part 1: Heat Release Rate (Cone Calorimeter Method) and Smoke Production Rate (Dynamic Measurement). International Organization for Standardization, Geneva, Switzerland.
ISO, 2007. ISO 21887:2007. Durability of Wood and Wood-Based Products – Use Classes. International Organization for Standardization, Geneva, Switzerland.
ISO, 2008. ISO 15686-8:2008. Buildings and Constructed Assets – Service-Life Planning – Part 8: Reference Service Life and Service-Life Estimation. International Organization for Standardization, Geneva, Switzerland.
ISO, 2010a. EN ISO 11925-2:2010. Reaction to Fire Tests – Ignitability of Products Subjected to Direct Impingement of Flame – Part 2: Single-flame Source Test. International Organization for Standardization, Geneva, Switzerland.
ISO, 2010b. EN ISO 9239-1:2010. Reaction to Fire Tests for Floorings – Part 1: Determination of the Burning Behaviour Using a Radiant Heat Source. International Organization for Standardization, Geneva, Switzerland.
ISO, 2012. ISO 10077-2:2012. Thermal Performance of Windows, Doors and Shutters – Calculation of Thermal Transmittance – Part 2: Numerical Method for Frames. International Organization for Standardization, Geneva, Switzerland, 36 p.
ISO, 2015. ISO 22007-2:2015. Plastics – Determination of Thermal Conductivity and Thermal Diffusivity – Part 2: Transient Plane Heat Source (Hot Disc) Method. International Organization for Standardization, Geneva, Switzerland, 20 p.
Jankowska, A., Kozakiewicz, P., 2013. Comparison of thermal properties of selected wood species from Africa. Ann. WULS – SGGW, For. Wood Technol. 82, 335–338.
Jourez, B., Verheyen, C., Van Acker, J., 2012. Coconut Lumber for Wood Decks (*Cocos nucifera* L.): Decay Resistance Against Basidiomycetes Fungi, IRG/WP 12-10784. The International Research Group on Wood Protection, Stockholm. 9 p.
Kabir, M.F., Khalid, K.B., Daud, W.M., Aziz, S.H.A., 1997. Dielectric properties of rubber wood at microwave frequencies measured with an open-ended coaxial line. Wood Fiber Sci. 29, 319–324.
Kain, G., Charwat-Pessler, J., Barbu, M.-C., Plank, B., Richter, K., Petutschnigg, A., 2016. Analyzing wood bark insulation board structure using X-ray computed tomography and modeling its thermal conductivity by means of finite difference method. J. Compos. Mater. 50 (6), 795–806.
Kanter, K.R., 1957. The thermal properties of wood. Derev. Prom. 6 (7), 17–18.
Kaudewitz, P., 2016. Vergleichende Untersuchungen zur Akzeptanz von Verwitterungserscheinungen und Fäulnisschäden an Fassaden und Terrassen aus Holz. (Master Thesis). Leibniz University Hannover, Hannover, Germany.
Kirby, J.J.H., Rayner, A.D.M., 1989. The deterioration of thatched roofs. Int. Biodeterioration 25, 21–26.
Kol, S.H., 2009. Thermal and dielectric properties of pine wood in the transverse direction. BioResources 4 (4), 1663–1669.
Kol, S.H., Sefil, Y., 2011. The thermal conductivity of fir and beech wood heat treated at 170, 180, 190, 200, and 212°C. J. Appl. Polym. Sci. 121, 2473–2480.
Kollmann, F.F.P., Côte, W.A.J., 1968. Physics of wood. In: Principles of Wood Science and Technology: I Solid Wood. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 160–291.
König, J., 2000. Thermal and mechanical properties of timber and some other materials used in light timber frame constructions. In: CIB W18 Meeting Delft.

Koskinen, O.M., Husman, T.M., Meklin, T.M., Nevalainen, A.I., 1999. The relationship between moisture or mould observations in houses and the state of health of their occupants. Eur. Respir. J. 14, 1363–1367.

Krabbenhøft, K., 2003. Moisture Transport in Wood. A Study of Physical Mathematical Models and Their Numerical Implementation. Department of Civil Engineering, Technical University of Denmark, Copenhagen.

Krabbenhøft, K., Damkilde, L., 2004. A model for non-Fickian moisture transfer in wood. Mater. Struct. 37, 615–622.

Küch, W., 1943. Der Einfluß des Feuchtigkeitsgehaltes auf die Festigkeit von Voll-und Schichtholz. Holz Roh Werkst. 6, 157–161.

Kutnik, M., 2013. Focus on European Standardisation. Towards a Revision of the EN350 Natural Durability Standard: A Different Approach to the Inherent Resistance and Performance of Wood and Wood-Based Materials, IRG/WP/13-10811. The International Research Group on Wood Protection, Stockholm. 9 p.

Kymäläinen, H.R., Sjöberg, A.M., 2008. Flax and hemp fibres as raw materials for thermal insulations. Build. Environ. 43, 1261–1269.

Kymäläinen, H.R., Hautala, M., Kuisma, R., Pasila, 2001. Capillarity of flax/linseed (*Linum usitatissimum* L.) and fibre hemp (*Cannabis sativa* L.) straw fractions. Ind. Crop. Prod. 14, 41–50.

Lesar, B., Gorišek, Ž., Humar, M., 2009. Sorption properties of wood impregnated with boron compounds, sodium chloride and glucose. Dry. Technol. 27, 94–102.

LeVan, S., Holmes, C.A., 1986. Effectiveness of fire-retardant treatments for shingles after 10 years of outdoor weatheringResearch Paper FPL 474.

Li, W., Van den Bulcke, J., De Windt, I., Van Loo, D., Dierick, M., Brabant, L., Van Acker, J., 2013. Combining electrical resistance and 3-D X-ray computed tomography for moisture distribution measurements in wood products exposed in dynamic moisture conditions. Build. Environ. 67, 250–259.

Li, W., Van den Bulcke, J., De Windt, I., Dhaene, J., Van Acker, J., 2016. Moisture behavior and structural changes of plywood during outdoor exposure. Eur. J. Wood Wood Prod. 74 (2), 211–221.

Lin, R.T., 1967. Review of the electrical properties of wood and cellulose. For. Prod. J. 17, 54–61.

Linseis, 2016. www.linseis.com (accessed 23.06.16).

MacLean, J.D., 1941. Thermal conductivity of wood. Heat. Piping Air Cond. 13, 380–391.

Mathis, N., 2000. Transient thermal conductivity measurements: comparison of destructive and nondestructive techniques. High Temp. High Pressures 32, 321–327.

Mehlich, R.T., 2009. Determination of Moisture Loads on Differently Sized Wooden Components Exposed Outdoors (Bachelor Thesis). Leibniz University Hannover, Hannover.

Meinlschmidt, P., 2016. Technology For Wood-Based-Materials. Fraunhofer Institute for Wood Research, Wilhelm-Klauditz-Institut WKI. http://www.wki.fraunhofer.de/en/departments/vst/profile/research-projects/thermal-conductivity-insulating-renewable-materials.html (accessed 23.06.16).

Merakeb, S., Dubois, F., Petit, C., 2009. Modeling of the sorption hysteresis for wood. Wood Sci. Technol. 43, 575–589.

Meyer, L., Brischke, C., 2015. Fungal decay at different moisture levels of selected European-grown wood species. Int. Biodeterior. Biodegrad. 103, 23–29.

Meyer, L., Brischke, C., Pilgård, A., 2012. Moisture Performance Based Wood Durability Testing, IRG/WP/12-20495. The International Research Group on Wood Protection, Stockholm.

Militz, H., Bloom, C., 2000. The Use of Lap-Joints in Natural Durability Testing: Moisture Content Development During 36 Months Outside Exposure Trials, IRG/WP/00-20217. The International Research Group on Wood Protection, Stockholm.

Mortensen, A., 2007. Concise Encyclopedia of Composite Materials, second ed. Elsevier Science, Amsterdam, Netherlands, 1050 p.

Netzsch, 2016. Heat Flow Meter – HFM 436 Lambda. http://www.paralab.pt/sites/default/files/pdf/HFM_436_Lambda_E_1013.pdf (accessed 23.06.16).

Ngô, C., Natowitz, J.B., 2016. Our Energy Future: Resources, Alternatives, and the Environment, second ed. John Wiley & Sons Inc., Chichester, New York, Brisbane, Toronto, Singapore.

Niemz, P., Sonderegger, W., 2011. Untersuchungen zur Wärmeleitung von Vollholz und Werkstoffen auf Vollholzbasis, wesentliche Einflussfaktoren. Bauphysik 33 (5), 299–305.

Nilsson, T., 1976. Soft rot fungi – decay patterns and enzyme production. Mater. Org. 3, 103–112.

Nilsson, T., 1985. Defining Decay Types – A Proposal for Discussion, Document No. IRG/WP/1264. The International Research Group on Wood Preservation, Stockholm, Sweden, 7 p.

Nilsson, T., Holt, D., 1983. Bacterial attack occurring in the S2 layer of wood fibres. Holzforschung 37, 107–108.

Nore, K., Blocken, B., Jelle, B.P., Thue, J.V., Carmeliet, J., 2007. A dataset of wind-driven rain measurements on a low-rise test building in Norway. Build. Environ. 42, 2150–2165.

Norman, D.A., 2002. Emotion and design: attractive things work better. Interact. Mag. ix (4), 36–42.

Nussbaum, R.M., 1988. The effect of low concentration fire retardant impregnations on wood charring rate and char yield. J. Fire Sci. 6, 290–307.

Nyrud, A.Q., Roos, A., Rødbotten, M., 2008. Product attributes affecting consumer preference for residential deck materials. Can. J. For. Res. 38, 1385–1396.

Osgood, C.E., Suci, G.J., Tannenbaum, P.H., 1957. The Measurement of Meaning. University of Illinois Press, Champaign, IL, USA.

Östman, B., Boström, L., 2015. Fire protection ability of wood coverings. Fire Technol. 51, 1475–1493.

Östman, B., Tsantaridis, L., 2016. Fire retardant treated wood products – properties and uses. In: 47th IRG Annual Meeting, Lisbon, Portugal, 15–19 May.

Östman, B., Voss, A., Hughes, A., Hovde, P.J., Grexa, O., 2001. Durability of fire retardant treated wood products at humid and exterior conditions – review of literature. Fire Mater. 25, 95–104.

Östman, B., et al., 2010. Fire Safety in Timber Buildings – European Guideline. SP Report 2010:19, Stockholm, Sweden.

Palanti, S., Pizzo, B., Feci, E., Fiorentino, L., Torniai, A.M., 2010. Nutritional requirements for larval development of the dry wood borer *Trichoferus holosericeus* (Rossi) in laboratory cultures. J. Pest. Sci. 83 (2), 157–164.

Paradis, S., Guibal, D., Vernay, M., Beauchêne, J., Brancheriau, L., Châlon, I., Daigremont, C., Détienne, P., Fouquet, D., Langbour, P., Lotte, S., Méjean, C., Thévenon, M.F., Thibaut, A., Gérard, J., 2011. Tropix 7.0: Caractéristiques technologiques de 245 essences tropicales et tempérées. CIRAD, Montpellier, France. ISBN: 978-2-87614-680-8. http://tropix.cirad.fr/.

Piipari, R., Keskinen, H., 2005. Agents causing occupational asthma in Finland in 1986–2002: cow epithelium bypassed by moulds from moisture-damaged buildings. Clin. Exp. Allergy 35, 1632–1637.

Pohleven, F., 2015. Prednosti i perspektiva gradnje drvenih kuća: iskustva iz Slovenije. (Advantages of the wooden houses. Experiences from Slovenia). Drvo-tehnika 12, 54–55.

Princes Risborough Laboratory, 1972. Laboratory Tests of Natural Durability Decay Resistance of Timber. Building Research Establishment, England, 28 p. (Timberlab Papers 50).

Råberg, U., Edlund, M.L., Terziev, N., Land, C.J., 2005. Testing and evaluation of natural durability of wood in above ground conditions in Europe – an overview. J. Wood Sci. 51, 429–440.

Ramananantoandro, T., Ramanakoto, M., Rajemison, A., Eyma, F., 2013. Relationship between density and aesthetic attributes of wood and preference of Malagasy consumers. Ann. For. Sci. 70, 649–658.

Rapp, A.O., Peek, R.D., Sailer, M., 2000. Modelling the moisture induced risk of decay for treated and untreated wood above ground. Holzforschung 54 (2), 111–118.

Rayner, A., Boddy, L., 1988. Fungal Decomposition of Wood. Its Biology and Ecology. John Wiley & Sons, Chichester, New York, Brisbane, Toronto, Singapore, 587 p.

Rice, R.W., Shepard, R., 2004. The thermal conductivity of plantation grown white pine (*Pinus strobus*) and red pine (*Pinus resinosa*) at two moisture content levels. For. Prod. J. 54 (1), 92–94.

Rowley, F.B., 1933. The heat conductivity of wood at climatic temperature differences. Heat. Piping Air Cond. 5, 313–323.

Rowley, F.B., Algren, A.B., 1937. Thermal conductivity of building materials. University of Minnesota, Minneapolis.

Sailer, M.F., van Nieuwenhuijzen, E.J., Knol, W., 2010. Forming of a functional biofilm on wood surfaces. Ecol. Eng. 36, 163–167.

Sandak, J., Negri, M., 2005. Wood surface roughness – what is it? In: Lachenmayr, G., Scholz, F. (Eds.), Proceedings of the 17th International Wood Machining Seminar, 26–28 September, Rosenheim, Germany, pp. 242–250.

Sandak, J., Riggio, M., Sandak, A., Santoni, I., 2015a. What is superb wood surface? Defining user preferences and service life expectations. For. Prod. J. 65 (3–4), S68–S73.

Sandak, J., Sandak, A., Riggio, M., 2015b. Multivariate analysis of multi-sensor data for assessment of timber structures: principles and applications. Constr. Build. Mater. 101 (2), 1172–1180.

Sandak, J., Sandak, A., Riggio, M., 2015c. Bio-based building materials: aesthetical service life and customer's environmental conciseness. In: Kutnar, A., Burnard, M., Schwarzkopf, M., Simmons, A. (Eds.), Proceedings of the 1st Conference of COST Action FP1407 Life Cycle Assessment, EPDs and Modified Wood, 25–26 August, Koper, Slovenia. pp. 14–15.

Scheffer, T.C., 1971. A climate index for estimating potential for decay in wood structures above ground. For. Prod. J. 21 (10), 25–31.

Scheffer, T.C., Morrell, J., 1998. Natural Durability of Wood: A Worldwide Checklist of Species. Forest Research Laboratory, Oregon State University. 58 p. (Research Contribution 22).

Schmid, J., König, J., Just, A., 2012. The reduced cross-section method for the design of timber structures exposed to fire—background, limitations and new developments. Struct. Eng. Int. 22 (4), 514–522.

Schmid, J., Just, A.A., Klippel, M., Fragiacomo, M., 2015. The reduced cross-section method for evaluation of the fire resistance of timber members: discussion and determination of the zero-strength layer. Fire Technol. 51 (6), 1285–1309.

Schmid, J., Santomaso, A., Brandon, D., Wickström, U., Frangi, A., 2016. Timber under real fire conditions – the influence of oxygen content and air velocity on the charring behaviour. In: Conference Paper, World Conference of Timber Engineering, WCTE, Vienna, Austria.

Sell, J., Feist, W.C., 1986. Role of density in the erosion of wood during weathering. For. Prod. J. 36, 57–60.

Siau, J.F., 1971. Flow in wood. Syracuse Wood Science Series, Syracuse University Press, New York.

Siau, J.F., 1995. Wood – Influence of Moisture on Physical Properties. Dept. of Wood Science and Forest Products, Virginia Polytechnic Institute and State University, Blacksburg, VA.
Singh, J., White, N., 1997. Timber decay in buildings: pathology and control. J. Perform. Constr. Facil. 11, 3–12.
Sirois, F., Grilli, F., 2015. Potential and limits of numerical modelling for supporting the development of HTS devices. Supercond. Sci. Technol. 28, 043002.
Sonderegger, W., Niemz, P., 2009. Thermal conductivity and water vapour transmission properties of wood-based materials. Eur. J. Wood Wood Prod. 67, 313–321.
Sonderegger, W., Hering, S., Niemz, P., 2011. Thermal behaviour of Norway spruce and European beech in and between the principal anatomical directions. Holzforschung 65 (3), 369–375.
Steinhagen, H.P., 1977. Thermal Properties of Wood, Green or Dry, from −40° to +100° C: A Literature Review: USDA Forest Service General Technical Report FPL-9. Forest Products Laboratory, Madison, WI.
Stienen, T., Schmidt, O., Huckfeldt, T., 2014. Wood decay by indoor basidiomycetes at different moisture and temperature. Holzforschung 68, 9–15.
Studhalter, J., 2013. Innenraumbekleidung und Brandrisiko. In: HolzBauSpezial Akustik & Brandschutz 2013, Internationales Holzbau-Forum IHF 2013, Garmisch-Partenkirchen, Kongresszentrum, 4–6 Dez. 2013, German.
Suleiman, M.B., Larfeldt, J., Leckner, B., Gustavsson, M., 1999. Thermal conductivity and diffusivity of wood. Wood Sci. Technol. 33 (6), 465–473.
Suttie, E., Brischke, C., Englund, F., Heisel, E., Jermer, J., Lorenzo, D., Polášek, M., Thelandersson, S., Van Acker, J., 2013. Performance Standards for Wood in Construction – Delivering Customer Service Life Requirements, IRG/WP/13-20537. The International Research Group on Wood Protection, Stockholm. 18 p.
Tannert, T., Berger, R., Vogel, M., Müller, A., 2011. Remote moisture monitoring of timber bridges: a case study. In: Proceedings of the 5th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-5). pp. 11–15.
Tavisto, M., Kuisma, R., Pasila, A., Hautala, M., 2003. Wetting and wicking of fibre plant straw fractions. Ind. Crop. Prod. 18, 25–35.
TenWolde, A., McNatt, J.D., Krahn, L., 1988. Thermal Properties of Wood and Wood Panel Products for Use in Buildings. Oak Ridge National Laboratory, Madison, WI.
Time, B., 1998. Hygroscopic Moisture, Transport in Wood (Doctoral Thesis). Norwegian University of Science and Technology, Trondheim.
Ugovšek, A., Šubic, B., Rep, G., Humar, M., 2015. Thermally modified wood – applicable material for passive windows – theory and practise. In: Proceedings of 19th International Passive House Conference, Leipzig, Germany.
Ulvcrona, T., 2006. Impregnation of Norway Spruce (*Picea abies* L. Karst.) Wood with Hydrophobic Oil (Doctoral Thesis). Swedish University of Agricultural Sciences, Faculty of Forest Science, Umeå.
Van Acker, J., Stevens, M., 2003. Biological durability of wood in relation to end-use – part 2: the use of an accelerated outdoor L-joint performance test. Holz Roh Werkst. 61 (2), 125–132.
Van Acker, J., Militz, H., Stevens, M., 1999. The significance of accelerated laboratory testing methods determining the natural durability of wood. Holzforschung 53 (5), 449–458.
Van Acker, J., Stevens, M., Carey, J., Sierra-Alvarez, R., Militz, H., LeBayon, I., Kleist, G., Peek, R.D., 2003. Biological durability of wood in relation to end-use. Holz Roh Werkst. 61, 35–45.
Van Acker, J., Van den Bulcke, J., De Boever, L., 2010. The Biological Durability Approach for Wood Product Performance and Service Life Prediction, IRG/WP/10-20457. The International Research Group on Wood Protection, Stockholm, 22 p.

Van Acker, J., Michon, S., Van den Bulcke, J., De Windt, I., Van Swaay, B., Stevens, M., 2011. Limited Variability in Biological Durability of Thermally Modified Timber Using Vacuum Based Technology, IRG/WP/11-40567. The International Research Group on Wood Protection, Stockholm.

Van Acker, J., De Windt, I., Li, W., Van den Bulcke, J., 2014a. Critical Parameters on Moisture Dynamics in Relation to Time of Wetness as Factor in Service Life Prediction, IRG/WP/14-20555. The International Research Group on Wood Protection, Stockholm.

Van Acker, J., Van den Bulcke, J., De Windt, I., Li, W., Defoirdt, N., 2014b. Service life concept for wood products used in exterior out of ground contact conditions. In: Proceedings of AWPA's 110th Annual Meeting, Newport Beach, California.

Van Acker, J., De Windt, I., Li, W., Van den Bulcke, J., 2014c. Critical Parameters on Moisture Dynamics in Relation to Time of Wetness as Factor in Service Life Prediction, IRG/WP/14-20555. The International Research Group on Wood Protection, Stockholm. 22 p.

Van den Bulcke, J., Van Acker, J., De Smet, J., 2009. An experimental set-up for real-time continuous moisture measurements of plywood exposed to outdoor climate. Build. Environ. 44 (12), 2368–2377.

Van den Bulcke, J., De Windt, I., Defoirdt, N., De Smet, J., Van Acker, J., 2011. Moisture dynamics and fungal susceptibility of plywood. Int. Biodeterior. Biodegrad. 65 (5), 708–716.

Van den Bulcke, J., De Windt, I., Brischke, C., Welzbacher, C.R., Rapp, A.O., Van Acker, J., 2013. Statistical Analysis of Durability Tests – Part 2: Principles of Time-to-Failure and Application on Field Test Data. The International Research Group on Wood Protection, Stockholm. 13 p.

Van den Bulcke, J., Cookson, L., De Windt, I., Li, W., Van Acker, J., 2014. Statistical Analysis of 40 Years of Preservative In-Ground Stake Testing in Australia, IRG/WP/14-20552. The International Research Group on Wood Protection, Stockholm.

Vay, O., Obersriebnig, M., Müller, U., Konnerth, J., Gindl-Altmutter, W., 2013. Studying thermal conductivity of wood at cell wall level by scanning thermal microscopy (SThM). Holzforschung 67 (2), 155–159.

Vay, O., De Borst, K., Hansmann, K., Teischinger, A., Müller, U., 2015. Thermal conductivity of wood at angles to the principal anatomical directions. Wood Sci. Technol. 49, 577–589.

Vereecken, E., Roels, S., 2012. Review of mould prediction models and their influence on mould risk evaluation. Build. Environ. 51, 296–310.

Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., Lähdesmäki, K., 2010. Moisture and bio-deterioration risk of building materials and structures. J. Build. Phys. 33, 201–224.

Vololonirina, O., Coutand, M., Perrin, B., 2014. Characterization of hygrothermal properties of wood-based products – impact of moisture content and temperature. Constr. Build. Mater. 63, 223–233.

Vosteen, H.-D., Schellschmidt, R., 2003. Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rock. Phys. Chem. Earth Parts A/B/C 28 (9–11), 499–509.

Waltjen, T., 2003. Wärmeansprüche des Menschen. Physikalische, physiologische, psychologische und soziale Bedingungen für thermische Behaglichkeit. In: IBO—Österreichisches Institut für Baubiologie und -ökologie, Vienna, Austria.

Wangaard, F.F., 1940. Transverse thermal conductivity of wood. Heat. Piping Air Cond. 12, 459–464.

Wei, D., Schmidt, O., Liese, W., 2013. Durability test of bamboo against fungi according to EN standards. Eur. J. Wood Wood Prod. 71 (5), 551–556.

Welzbacher, C.R., Wehsener, J., Rapp, A.O., Haller, P., 2008. Thermo-mechanical densification combined with thermal modification of Norway spruce (*Picea abies* Karst) in industrial scale – dimensional stability and durability aspects. Holz Roh Werkst. 66, 39–49.

Wenger, K.F., 1984. Forestry Handbook, second ed. Wiley-Interscience, Chichester, New York.

Wilkes, K.E., 1979. Thermophysical properties data base activities at Owens-Corning fiberglas. In: Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of Exterior Envelopes of Buildings, Kissimmee, FL, pp. 662–677.

Willeitner, H., Peek, R.D., 1997. The Natural Durability Story, IRG/WP/97-20119. The International Research Group on Wood Protection, Stockholm. 14 p.

Williams, J.R., Sawyer, G.S., Cragg, S.M., Simm, J., 2005. A questionnaire survey to establish the perceptions of UK specifiers concerning the key material attributes of timber for use in marine and fresh water engineering. J. Inst. Wood Sci. 17, 41–50.

Winandy, J.E., 1995. Effects of waterborne preservative treatment on mechanical properties: a review. In: Proceedings of the 91st Annual Meeting of the American Wood-Preservers' Association, May 21–24, New York.

Yapici, F., Ozcifci, A., Esen, R., Kurt, S., 2011. The effect of grain angle and species on thermal conductivity of some selected wood species. BioResources 6 (3), 2757–2762.

Yu, Z.-T., Xu, X., Fan, L.-W., Hu, Y.-C., Cen, K.-F., 2011. Experimental measurements of thermal conductivity of wood species in china: effects of density, temperature, and moisture content. For. Prod. J. 61 (2), 130–135.

Zelinka, S.L., Glass, S.V., Stone, D.S., 2008. A percolation model for electrical conduction in wood with implications for wood-water relations. Wood Fiber Sci. 40, 544–552.

Zelinka, S.L., Gleber, S.C., Vogt, S., Rodríguez López, G.M., Jakes, J.E., 2015. Threshold for ion movements in wood cell walls below fiber saturation observed by X-ray fluorescence microscopy (XFM). Holzforschung 69, 441–448.

Zhao, J., Jia, X., Cai, Y., 2016. Inverse determination of thermal conductivity in lumber based on genetic algorithms. Holzforschung 70 (3), 235–241.

Zuo, H., Hope, T., Jones, M., 2014. Tactile aesthetics of materials and design. In: Karana, E., Pedgley, O., Rognoli, V. (Eds.), Material Experience. Fundamentals of Material and Design. Elsevier, Oxford.

This page intentionally left blank

Performance of buildings

6

S.L. Bardage
RISE Research Institutes of Sweden, Stockholm, Sweden

6.1 Introduction

Performance of buildings refers to the efficiency of functionality and its impact on environment and users. Architectural design and engineering, choice of building materials, environment at location, energy consumption and sustainability are important components that will all influence building performance.

Europe has set a course towards a more sustainable and bio-based society since the beginning of the century. The increase in use of sustainable bio-based building materials is a key growth area for the construction sector and for the built environment. Many existing bio-based alternatives to conventional non-bio-based building materials hold properties that impact positively on building physics by often being lighter, on energy consumption by providing better insulation and on human well-being by influencing our senses. Even though bio-based building materials have been commonly used in many cultures throughout human history, the rapid development of our civilisation in the last centuries led to the development of modern construction systems based on steel, concrete and petroleum-derived materials. The shift from conventional construction materials and design back to more bio-based and sustainable systems requires knowledge on and understanding of available bio-based building materials' capability.

This chapter covers important aspects linked to material performance, potential use and advantages of available bio-based building materials. Nevertheless, the ongoing rediscovering of ancient bio-based materials and building techniques and development of new and sophisticated bio-based products for construction will offer many alternatives to meet the needs and requirements of building sector and of the society.

6.2 Building physics

*P. Faria**, *A. Brás*[†,‡]
*CERIS and NOVA University of Lisbon, Caparica, Portugal
[†]NOVA University of Lisbon, Caparica, Portugal
[‡]Current affiliation: Liverpool John Moores University, Liverpool, United Kingdom

6.2.1 Introduction

Building physics can be defined as the 'applied science that studies the hygrothermal, acoustical and light-related properties of building components' (Hens, 2007), building areas and building assemblies. Their knowledge is imperative to design high-performance buildings that are healthy, comfortable, durable, energy-efficient, affordable and, therefore, eco-efficient.

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00006-9
© 2017 Elsevier Ltd. All rights reserved.

The physical behaviour of a building depends not only on the building technologies that are used but also mainly on the materials that are applied. From a thermal behaviour point of view, there are three principal properties typically used to describe the heat transport through a material:

(a) Thermal conductivity
(b) Specific heat
(c) Thermal diffusivity

However, the knowledge of the hygrothermal functional properties of all construction materials used in the building envelope (including bio-based materials) is also required for any predictive modelling of its behaviour. These properties include (Hall *et al.*, 2012; Freitas *et al.*, 2012) the following:

- Specific heat capacity (J/(kg K)) – the amount of energy required to raise one unit of mass by one Kelvin and at constant pressure, which can also be converted to volumetric heat capacity by multiplying by the material bulk density.
- Moisture-content-dependent heat capacity (J/(kg K)) – the heat capacity of a porous material increases significantly with the degree of saturation, since the specific heat capacity of water is comparably high and so is a function of moisture content for partially – or fully – saturated materials.
- Bulk porosity (–) – the ratio of the volume of pore space to the total volume of a material.
- Bulk density (kg/m^3) – the ratio of dry mass to total volume.
- Thermal conductivity (W/(m K)) – describes the material's ability to transmit heat via conduction.
- Thermal diffusivity (m^2/s) – the thermal conductivity divided by density and specific heat capacity at constant pressure.
- Moisture-content-dependent thermal conductivity (W/(m K)) – the thermal conductivity increases significantly with the degree of saturation and, therefore, is a function of moisture content for partially or fully saturated materials.
- Water vapour diffusion resistance factor (–) – the ratio of the vapour diffusion resistance of air to the vapour diffusion resistance of the porous material.
- Moisture storage function – the isothermal relationship between the equilibrium moisture content (*EMC*) of a porous material at each value of *RH* from 0% to 100%, also referred to as the 'sorption isotherm'.
- Water absorption coefficient (kg/(m^2 s$^{1/2}$)) – the rate of water (mass) absorption against the square root of elapsed time due to capillarity in a porous material.

Currently, the European market of insulating materials is dominated by inorganic materials and organic foams, which account for 60% and 27% of the market, respectively, whereas natural fibres (as cork) and new technology materials account for less than 13% all together (Al-Homoud, 2005; Papadopoulos, 2005). The manufacture of thermo-insulating materials, such as inorganic materials and organic foams, is quite demanding as regards consumption of energy, raw materials and cost. Threats of uncertain petroleum supply in the near future together with environmental concerns enhances the need of finding available alternative material resources. Renewable resources seem to be the advantageous alternative, not loading the environment on the condition of consequent processing with low energy demand.

Natural and bio-based construction materials represent a promising solution for optimising buildings' environmental sustainability. The combination of bio-materials such as kenaf, hemp, flax, jute, henequen, pineapple leaf, coconut, wood, cork, cane, cardboard or sisal with polymer matrices from both non-renewable and renewable resources to produce composite materials are emerging as a viable alternative to glass-fibre-reinforced composites, especially in building product applications. These are considered effective raw materials for producing insulating panels at a reduced cost.

Bio-based materials have been studied by several authors, and a high number of papers that assess the thermal properties can be mentioned (Limam *et al.*, 2016; Ramesh, 2016; Kamke and Zylkowski, 1989; Harada *et al.*, 1998; Suleiman *et al.*, 1999; Asdrubali *et al.*, 2016a,6b; Cardoso *et al.*, 2015a,b; Faria *et al.*, 2016; Brás *et al.*, 2013, 2014a; Silva *et al.*, 2005; Kang *et al.,* 2015).

Natural fibres are becoming increasingly popular thanks to several advantages: low mass densities, cell structures, low thermal conductivity, high sound-absorption properties, no harmful effects on health, large availability and sustainability (low embodied energy and low-greenhouse-gas emissions for the production of the material and also the fact that they are often agriculture wastes or by-products) (Berardi and Iannace, 2015; Ricciardi *et al.*, 2014; Ekici *et al.*, 2012; Chau *et al.*, 2015; Proietti *et al.*, 2013). They generally have good thermal-insulation properties and sometimes also acoustic, similarly to traditional porous materials. Insulating panels made of other materials such as sugar cane and rice husk have higher thermal conductivities (about 0.045–0.055 W/(m K)), but they are also interesting because of the large availability and the low costs (Asdrubali *et al.*, 2015).

Natural fibres as kenaf, wood, cork, cane, cardboard, sheep wool, etc. are considered effective raw materials for producing insulating panels at a reduced cost and particularly with low embodied energy. In the field of composites, as they are generally made with polymeric resins, the major drawback of natural-fibre-based composites is the incompatibility between the hydrophilic natural fibres and the hydrophobic polymeric matrices. Plant fibres are the most popular of the natural fibres, used as reinforcement in fibre-reinforced composites. Plant fibres include bast or stem fibres, leaf fibres, seed, fruit, wood, cereal straw, cereal husk and other grass fibres (Fig. 6.1).

6.2.2 Hygrothermal properties of bio-based building materials

Regarding hygrothermal properties, there is still a huge opportunity to develop research studies for bio-based materials. In order to maintain a healthy indoor air quality, the use of hygroscopic materials should be promoted since they contribute to the stabilisation of fluctuations in relative humidity (RH) (Simonson *et al.*, 2004a; Shea *et al.*, 2012).

According to Holcroft and Shea (2013), all natural-fibre insulation materials are hygroscopic. Within their structure, they have hydroxyl groups that will bond hydrogen with water molecules. The RH of their environment has a huge influence in the quantity of water adsorbed, which means that they are able to stabilise the humidity of a room by adsorbing when the RH increases and desorbing as it decreases.

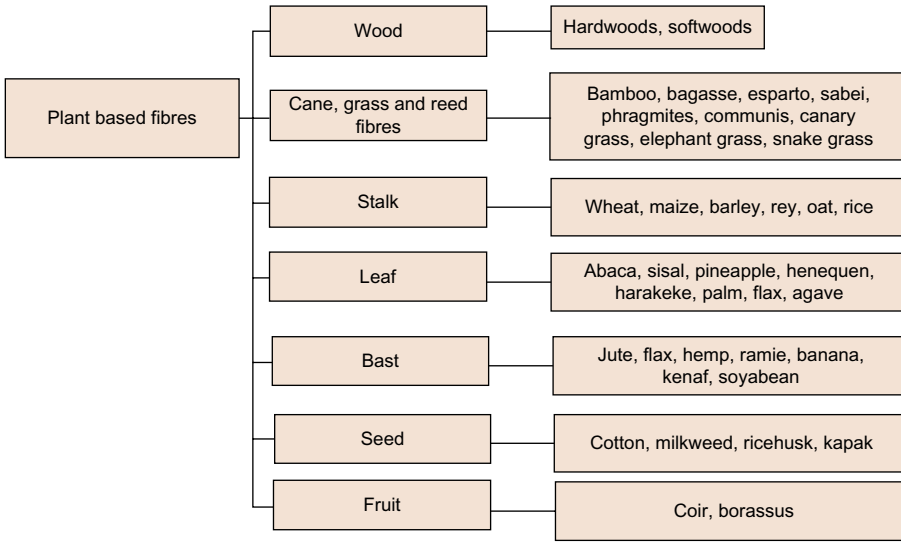


Fig. 6.1 Classification of natural fibres.
Based on Bledzki, A., Sperber, V., Faruk, O., 2002. Natural and wood fibre reinforcement in polymers. Rapra. Rev. Rep. 13 (8), 1–144; Baillie, C., 2004. Green Composites: Polymer Composites and the Environment. CRC Press, Boca Raton, FL.; Pickering, K.L., 2008. Properties and Performance of Natural Fibre Composites. Woodhead Publishing Ltd., Cambridge.

The moisture content of a plaster is in permanent dynamic equilibrium with the environment dynamic (Laborel-Préneron *et al.*, 2016). Humidity buffering is a desirable property of a material to absorb water vapour from the air, when RH is high, and release this water as vapour when RH falls. This property can be quantified using the experimentally determined moisture buffer value (*MBV*). It indicates the amount of moisture uptake or release by a material when it is exposed to repeated daily variations in RH between two given levels. The MBVs of the materials are classified into the following categories: negligible (MBV, 0.0–0.2), limited (MBV, 0.2–0.5), moderate (MBV, 0.5–1.0), good (MBV, 1.0–2.0) and excellent (MBV, 2.0-upwards) (Latif *et al.*, 2015).

Fig. 6.2 presents several moisture buffer capacities (g/m^2), which is the ability of each sample to adsorb and desorb water vapour determined by exposing it to a cycle of step changes in RH and was collected from the existing state of the art.

From a building perspective, moisture buffering in the entire room is related to exposure areas of the surface materials, moisture load, ventilation rate and indoor climate. A novel probabilistic approach can be used for evaluating performance and select the best solutions for building design and retrofitting (Brás *et al.*, 2016). By this approach, for a convent building rehabilitation in Portugal, the use of bio-based earth plasters (formulated with clay-rich earth, sand and vegetal fibres) can be a solution due to their hygroscopic characteristics. In order to maintain a healthy indoor air quality inside classrooms, the use of this type of bio-based materials should be promoted since they contribute to the stabilisation of fluctuations in RH, and indoor comfort can increase 10% by increasing the

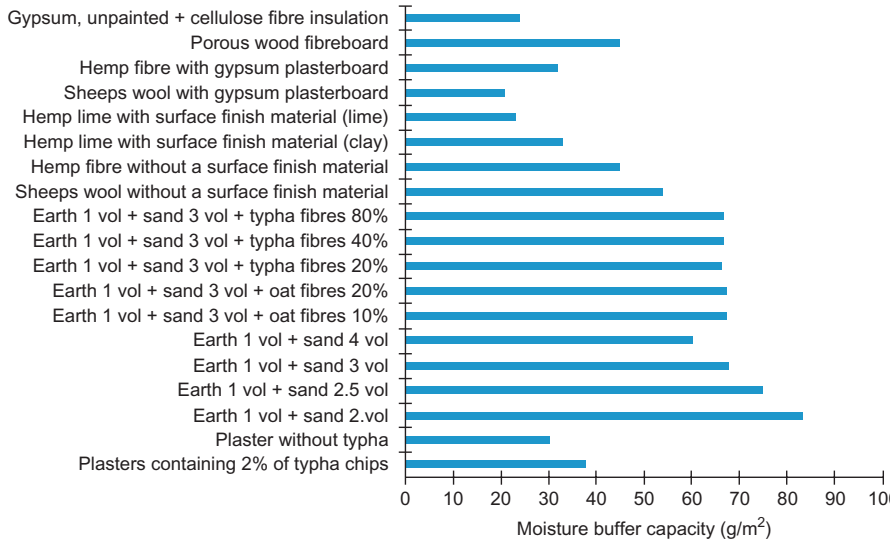


Fig. 6.2 Moisture buffer capacity of some bio-based materials (Lima and Faria, 2016; Holcroft and Shea, 2013; Salonvaara *et al.*, 2004).

MBV of the indoor surface. Nevertheless, susceptibility to biological development with the indoor conditions should also be studied and, if needed, controlled.

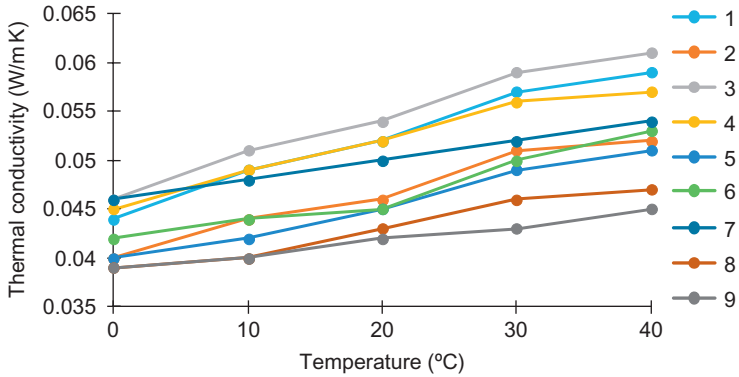
Korjenic *et al.* (2016) developed insulation materials based on natural fibres in particular technical hemp, flax and jute and their application into buildings. The researchers assessed hydrothermal behaviour of the developed materials, including computational simulation of behaviour of the optimal hemp-fibre-based material applied in a building with a green plant facade.

The main selected raw material resource for natural-based insulation materials was technical hemp (technical hemp produced in Austria, content of tetrahydrocannabinol is maximum of 0.3%), which was compared with other selected natural fibres – cultivated flax (from the Czech Republic) and jute (from Asia).

Nine compositions of insulation materials were designed. Determination of thermal conductivity coefficient of test specimens with dimension 300 × 300 mm was carried out at medium temperatures 0°C, +10°C, +20°C, +30°C, +40°C and thermal gradient 10 K. According to Fig. 6.3, it can be stated that test sets with higher bulk density showed a slightly change of thermal conductivity (at 0°C and 40°C) compared with test sets with lower bulk density.

Test specimens were also subjected to determination of balanced sorptive humidity at the temperature of 23 ± 0.5°C for RH 0%, 30%, 50%, 55%, 70% and 80% in accordance with European standard EN ISO 12571. The results show that, compared with other natural material (wood, sheep wool, etc.), the humidity sensitivity of insulation from technical hemp is lower (Chybík, 2009).

The dependence of the thermal conductivity on RH was also studied by Korjenic *et al.* (2016). The testing proved that content of humidity has crucial influence on the value of thermal conductivity coefficient. The results demonstrate that test specimens



Mixture	Type of fibre	Weight percentage of input components (%) Natural fibres	Binder fibres	Shives
1	Jute	68	20	12
2	Flax	68	20	12
3	Hemp	48	20	32
4	Hemp	68	20	12
5	Hemp	48	20	32
6	Hemp	48	20	32
7	Hemp	48	20	32
8	Hemp	64	20	16
9	Hemp	49	10	41

Fig. 6.3 Dependence of the thermal conductivity on temperature.
Based on Korjenic, A., Zach, J., Hroudová, J., 2016. The use of insulating materials based on natural fibers in combination with plant facades in building constructions. Energy Build. 116, 45–58.

show lower sensitivity in low and medium RH environments. Levels of sensitivity gradually increase with higher RH (>60%).

If the developed materials are exposed to an environment with RH up to 60%, no marked changes of thermo-insulating properties are observed. Based on evaluation of dependence of thermal conductivity on humidity of the material, it can be stated that no considerable changes of thermal conductivity take place up to 60% of humidity of the material.

Simões *et al.* (2016) assessed the influence of the penetration depth of hemp concrete with different binders. To optimise the RH passive regulation capacity, 5 cm hemp concrete should be provided.

Rahim *et al.* (2016) compared the behaviour of three bio-based materials: hemp concrete, flax concrete and rape straw concrete. The results showed that these materials have an interesting heat storage capacity and a low thermal conductivity, which

provides a good thermal behaviour. For a range of temperature from 10°C to 40°C, the effects of temperature and water content on thermal conductivity are important. The experimental results demonstrate that effect of the water content and temperature on thermal conductivity is important and hence should be considered. Experimental results show that the specific heat capacities for the three concretes are approximately 1100 J/(kg K). In addition, these materials show low thermal diffusivity, which leads to dampen heat diffusion from the outdoor ambiance.

6.2.3 Acoustic properties of bio-based building materials

Acoustic comfort has become more important as the urban population has moved into multioccupant dwellings. For sound to be produced, it is necessary to have a source of the sound, a means of its transmission and for it to be detected. Once a sound has been produced, it maybe transmitted through any medium capable of transmitting wavelengths, either atmospheric or through a material. The degrees to which a sound is detected is often linked to the frequencies involved, which has led to testing across a range of standardised frequencies, typically 250, 512, 1024 and 2048 Hz, respectively. An overview of the transmissive properties of bio-based materials was recently published (Zhu *et al.*, 2014).

According to Nurzynski (2015), it is difficult to find a simple relationship between acoustic and thermal insulation; some technical solutions that improve the thermal resistance of a panel can reduce the sound insulation. Any correlation may be derived for well-defined groups of homogeneous solid partitions with similar structure, but such dependencies are of little practical use. This enhances the need of having a holistic approach to provide a comfortable, tailor-made building meeting all requirements and expectations. All requirements and recommendations within the area of building physics should be coordinated to avoid any incoherence that can make different requirements conflicting and hardly applicable in practice. A good acoustic solution can be achieved with massive homogeneous partitions (high-acoustic-insulation properties due to high densities) and/or with insulating layers with high open porosity and incorporated air, but in order to also obtain good thermal resistance, this last hypothesis is preferable.

Nurzynski (2008) observed that the application of thermal insulating linings is effective for the thermal and sound insulation (for materials with high dynamic stiffness and internal damping), but in some cases, it produces negative effects by decreasing the sound insulation in a specific frequency range. The open-pore structure of some natural materials represents a disadvantage due to their high wettability, which means that they have to be protected against biological attacks (fungi, moulds, parasites, etc.) and fire. In a study regarding the thermal behaviour of natural-insulating materials in different humidity conditions (Zach *et al.*, 2013), it was observed that the reduction of wettability by the application of hydrophobic agents reduced the rate of degradation of the thermal-insulation properties: an increase of thermal conductivity (λ) by about 43% is typical in normal conditions (from the dried-up state to 80% of RH); however, the use of hydrophobic agents lowers the increase of λ to around 30%.

Porous materials with interconnected cavities – such as materials made of fibres or granules – are required to obtain good sound absorption behaviour and to increase sound insulation of walls or to reduce reverberation time at medium-high frequencies.

Since acoustic properties depend on frequency, direct comparisons cannot be easily performed such as for thermal properties.

Whilst the idea of using reed-based panels for thermal insulation is fairly well known and commercialised through the manufacture of Berger panels in countries such as Estonia (Stenman, 2008), it is only more recently that studies have been undertaken into the acoustic properties. Common reed bio-based panels for building envelopes were studied by Asdrubali *et al.* (2016a,b), and in particular, *Arundo donax*, which is mainly available in the Mediterranean Basin and Middle East Asia and probably also parts of Africa and southern Arabian Peninsula. This work showed very promising overall thermoacoustic behaviours were possible with the use of reed. It was shown that the geometry scarcely affected the thermal conductivity, which was around 0.05 W/(m K). Acoustic behaviour is strongly affected by the stalk configuration, for example, perpendicular, parallel or combined orientation with respect to the incident wave. The longitudinal stalk layout showed a significant sound absorption performance. For the optimisation of the panel field performance, the acoustic requirements should represent the panel design drivers, given the high sensitivity of the panel layout characteristics affecting the acoustic performance.

Asdrubali *et al.* (2016a,b) also tested the influence of the density and the thickness of the panels. Generally, the thermal performance of insulation materials decreases with the density increment. However, the trend for the reed panels seems to be the opposite. In fact, when the density increases, it means that the voids in the reed panels are filled by the stalks. Hence, the cavities of the stalks increase but the air between the reed stalks decreases, reducing the equivalent thermal conductivity of the panels. The measurements showed that for an increment around 15% of the density, there is an equivalent thermal conductivity improvement by around 9% (Asdrubali *et al.*, 2016a,b).

The experimental characterisation of such by-products achieved by the collection of spontaneous common reed vegetation showed that such selected greenery could represent a very promising material for both thermal and acoustic insulation in building walls and ceilings. In particular, due to fire resistance and durability constraints, the best solution so far could be common reed-based panels applied as filler of the air gaps in gypsum-based internal partitions or internal multilayer ceiling structures.

Ramesh (2016) presented a study regarding an overview of the developments made on kenaf-fibre-reinforced composites in terms of their market, manufacturing methods, matrix combinations, environmental effects and chemical treatments. Expanding on a previous review (Ramesh *et al.*, 2013), the kenaf-fibre-reinforced composite specimens in this review presented a higher degree of sound insulation than standard foam (Bruel and Kjaer foam is a commonly used standard reference sample for testing with a thickness of 25 mm, since it features high sound absorption but very low sound insulation). The kenaf composites suggested such isotropic panels could be used as sound barrier materials. The transmission loss (*TL*) is a dB value that represents the damping properties of a material, meaning the higher its value, the more the sound is attenuated. This study showed that in the low-frequency range of 100–800 Hz, the TL of an isotropic panel was controlled by panel stiffness and resonance, whilst, in the frequency range around 200–400 Hz, the resonance of the panels caused a sudden decrease of the TL.

Insulation corkboards (*ICB*) are made by natural bonding of cork granules, expanded by action of heat and pressure (see Section 2.7). The industrial production is carbon-free because the granules are cork wastes and the heat is generated by burning cork and wood powder collected during the industrial production of bottle stoppers and other cork products (Brás *et al.*, 2013). The size of cork granules can impact the acoustic performance (Maderuelo-Sanz *et al.*, 2014) as demonstrated by assessing by ISO standard 10534-2 (ISO (1998)) standard. By combining cork and various natural fibre, it is possible to create a range of ICB-type product with specific properties. The only issue with such practice is the transportation and ecological issues associated with other residual bio-based materials, such as coconut fibres.

Limam *et al.* (2016) studied wood, cork and their composites, especially sandwich assemblies of both materials. The aim of the study was to show the influence of the moisture on the values of the thermal properties of wood and cork. They observed that the average value of the thermal conductivity in the perpendicular direction was higher than the average value in parallel direction. For solid wood, a difference of 0.1 W/(m K) was obtained between the registered values on the two directions, whilst for laminated timber wood, it was 0.06 W/(m K), and for cork, it was 0.037 W/(m K).

Boards made of corn cob (Cardoso *et al.*, 2015a), rice husks or olive pit may provide an eco-efficient possibility (Fig. 6.4). The current challenge is to incorporate bio-based glues into bio-based composites (Cardoso *et al.*, 2015b) and to industrialise the processes.

6.2.4 Bio-based phase-change materials

Phase-change materials (*PCM*) are generally materials with large specific latent heat capacity. PCM used in buildings will typically melt and solidify within a range of 18–30°C and are normally contained in the building fabric. Through their melting/solidification, these materials are capable of absorbing and releasing up to 15 times more thermal energy than conventional (non-phase-change materials), making them useful components in maintaining thermal performance and comfort within modern buildings. The majority of commercially available PCMs are wax-based usually from non-renewable sources. Bio-based PCM can be produced from underused feedstock, such as soybean oil, and are significantly less flammable than paraffins (Fig. 6.5). Several studies (Kang *et al.*, 2015; Cui *et al.*, 2015; Cellat *et al.*, 2015) demonstrated

Fig. 6.4 Rice husk, corn cob and olive-pit-based insulation board samples.

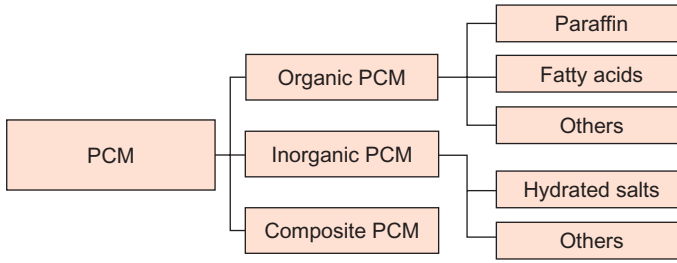


Fig. 6.5 Types of PCM.
Based on Kang, Y., Jeong, S., Wi, S., Kim, S., 2015. Energy efficient bio-based PCM with silica fume composites to apply in concrete for energy saving in buildings. Sol. Energy Mater. Sol. Cells 143, 430–434; Cui, Y., Xie, J., Liu, J., Pan, S., 2015. Review of phase change materials integrated in building walls for energy saving. Procedia Eng. 121, 763–770; Cellat, K., Beyhan, B., Güngör, C., Konuklu, Y., Karahan, O., Dündar, C., Paksoy, H., 2015. Thermal enhancement of concrete by adding bio-based fatty acids as phase change materials. Energy Build. 106, 156–163.

that bio-based PCM could be useful within building materials, such as mortar or concrete, because they improve the thermal properties of the material, and as a result, such materials should be considered for use in energy-efficient buildings.

Cui *et al.* (2015) presented a study including the PCM thermophysical properties, PCM types, PCM incorporation methods suitable for PCM walls and specific application methods of PCM walls. According to this study, the range of melting temperature varied between 19°C and 28°C for organic PCM and 25–35°C for inorganic PCM. The heat of fusion was almost within the scope of 120–280 kJ/kg regardless the type of PCM. The thermal conductivity was close to 0.2 W/(m K) for organic and 0.6 W/(m K) for inorganic PCM, whilst the density was from 700 to 900 kg/m^3 for organic and 1300–1800 kg/m^3 for inorganic PCM.

Fatty acids are derivatives of materials readily found in nature and labelled as bio-based. Binary mixtures of different fatty acids were studied by Cellat *et al.* (2015). Capric acid (*CA*), myristic acid (*MA*), lauric acid (*LA*) and palmitic acid (*PA*) were considered as candidate materials for building applications. Two binary mixtures of CA-LA and CA-MA were tested. The melting points of such fatty acid mixtures may further be adjusted, to agree with human-comfort-zone temperatures by regulating their compositions. Furthermore, potential advantages of fatty acids as thermal energy storage material are their smaller volume change during phase transitions, high latent heats per unit mass and suitable melting-temperature ranges.

Bio-based PCM are reported as significantly less flammable than paraffinic PCM (Kang *et al.*, 2015). PCM walls have a relatively good potential for energy saving; however, more research focusing on real full-scale buildings and real-operation conditions needs to be undertaken to prove the authenticity and reliability of current studies. The developed research shows that the application of PCM in walls needs to be combined with other media or devices so as to strengthen the overall application effect.

6.2.5 Conclusions on bio-based materials contributing to building physics

Several and very diverse bio-based materials can be used as building materials and contribute to the overall physical properties of the building. These are agriculture wastes from cork, corn, sunflower, olive pit, rice, oat, wheat and other cereals, invasive species like reed or Typha, or other bio-based materials produced on purpose such as hemp, sisal, flax, jute, kenaf and wood. Bio-based materials can be used in different ways, such as in aggregates of mortars and concretes; in aggregates in masonry blocks; as components of monolithic walls, namely, using earth as building material; as boards with only one type of bio-based material or associating more than one type; and as structure for lightweight walls.

Developments on natural bio-based glues and on industrial production of boards made of agriculture waste, with corn cob, rice husk, olive pit, sunflower waste, etc. would contribute to spread the use of this eco-efficient insulation boards.

The use of bio-based PCMs could be useful to include in building materials, such as mortar or concrete, because they improve the thermal properties of the material, and further research should focus on making bio-based PCM considered for use in eco-efficient buildings. Bio-based PCMs have influence on thermal comfort, but almost all the other bio-based materials used in different building elements can have influence not only on thermal comfort but also on hygrothermal equilibrium and on acoustic comfort. Hemp mortars and concretes and earth-based plasters present the highest moisture buffering capacities, which can strongly contribute for RH equilibrium indoor. Nevertheless, aspects concerning fire safety and susceptibility to mould and other biological anomalies need to be further investigated.

6.3 Energy efficiency

*P. Faria**, *A. Brás*[†,‡]
*CERIS and NOVA University of Lisbon, Caparica, Portugal
[†]NOVA University of Lisbon, Caparica, Portugal
[‡]Current affiliation: Liverpool John Moores University, Liverpool, United Kingdom

6.3.1 The need to reduce energy requirement in buildings

According to the European Commission (2012a,b), energy efficiency is the ratio of output of performance, service, goods or energy, to input of energy. In the buildings context, the reduction of the energy use and cutting down on waste (by means of finding new added values for it) leads to a decrease on the energy bills and make the energy supplies more secure.

Europe's objective is to consistently reduce greenhouse gas emissions up to 80%–95% in 35 years (European Commission, 2011). However, buildings account for around 40% of the total final energy consumption in Europe (Brás *et al.*, 2014b; Fouquet *et al.*, 2015). This enhances the need to reduce energy requirement to keep high indoor air quality and thermal comfort conditions.

Research and technology innovation regarding sustainable and efficient solutions to save energy and to improve indoor environmental quality in buildings represent a key scientific issue to be urgently addressed. Within the European Union, where bioeconomy is an important challenge in the Horizon 2020 Framework programme, a report was released by the European Commission in February 2012 (European Commission, 2012a,b) based on opinions and a consultation process that took place during 2011.

Environmentally friendly materials and passive solutions, in general, are optimal strategies to achieve this target. Therefore, the advantage of natural, sustainable and bio-based materials (Asdrubali *et al.*, 2016a,b) in buildings can be highlighted:

(a) Reduction of peak energy demand and cost for building sector (Ascione *et al.*, 2015)
(b) Mitigation of local climate change phenomena such as urban heat island (Salata *et al.*, 2015)
(c) Improvement of indoor acoustics and thermal performance (Barreneche *et al.*, 2016; Secchi *et al.*, 2016; Asdrubali *et al.*, 2016a,b)
(d) Reduction of the carbon emissions attributed to *HVAC* system operation (Rincón *et al.*, 2015)

Natural materials are already available and have limited postprocess impact. Their inner characteristics contribute to the minimisation of the environmental impact since they require less industrial and technology transformations than those of most common artificial materials. Some natural materials conveniently combine low embodied energy, low cost and intrinsic optimal characteristics to improve building thermoacoustic performance and comfort (Asdrubali *et al.*, 2015; Brás and Gomes, 2015; Brás, 2016).

Manufacture of currently used thermo-insulating materials is quite demanding regarding the consumption of energy, raw materials and cost. To overcome this, several studies are ongoing into locally sourced raw materials, of low environmental impact, suited for developing high-value products with superior performance (Korjenic *et al.*, 2016).

Materials based on natural resources, like cork, reed grass, straw, hay, linen, hemp or lichens have been used for thermal-insulation purposes for millenia. Much research has been carried out as well on the use of crop by-products such as straw, stalks or husks of cereals into adapted building applications (Madurwar *et al.*, 2013), although to date there are only a few commercially available products.

Currently, much of the state-of-the-art research has been focused on the use of natural-fibre reinforcement in composites (Sobral, 1990; Magniont *et al.*, 2012), the development of high- and medium-density boards (Halvarsson *et al.*, 2010) or straw-bale wall systems (Wall *et al.*, 2012). However, there is an increasing interest in their use in bio-based thermal-insulation materials.

6.3.2 Smart products and smart use of raw materials

6.3.2.1 Smart bio-based materials in the reduction of buildings energy use

The utilisation of natural resources, like common reed (Kobbing *et al.*, 2013) and other green materials (Asdrubali *et al.*, 2015), with intrinsically low environmental impact and satisfactory thermoacoustic insulation properties, represents a key research deal, even in low-cost constructions.

The advantage of the hygroscopic behaviour of bio-based materials on energy consumptions in buildings has been studied by some researchers. Osanyintola and Simonson (2006), for example, estimated the effect of hygroscopic materials on energy consumptions in buildings and that it may be possible to reduce heating- and cooling-energy consumption by up to 5% and 30%, respectively, when applying hygroscopic materials with well-controlled heating, ventilation and air-conditioning (HVAC) systems. They examined the effects of the heat of sorption by comparing two simulations of a 12 m^2 bedroom in a northern European climate, one with hygroscopic materials (wood fibreboard and cellulose insulation) and the other with no hygroscopic materials. Heating was set to maintain the room at 20–21°C during the heating season, and moisture levels were set to that created by two people sleeping at night. During occupation by two adults for 9 h each night (from 22:00 to 7:00), it was found that energy use was ≈10% lower in the room insulated with hygroscopic materials, due to heat of sorption. However, over the whole heating season, it was nearly equal because, when the RH decreased (i.e. when people left the room), the resulting evaporative cooling increased the energy use. Nevertheless, if heating controls were set to account for this, it is possible that an energy saving could be achieved.

From a building perspective, moisture buffering in the entire room is related to exposed areas of the surface materials, moisture load, ventilation rate and indoor climate. According to Osanyintola and Simonson (2006), moisture buffering may reduce energy use through both direct and indirect effects on heating load. Latent-heat exchanges caused by the adsorption and desorption of water vapour could be the direct cause on heating load. An indirect saving would be to achieve a healthy level of humidity with a lower ventilation rate or greater airtightness (Simonson *et al.*, 2004b), therefore losing less heated air to the outdoors and using less power to run the ventilation system. Qin *et al.* (2009) also investigated the effect of latent-heat exchanges on the heating load. A wooden structure with plasterboard coating was compared with a non-hygroscopic coating (aluminium foil) in an office space with 20 m^2, for which it was found that 6.5% less heating energy was required during occupation when including latent-heat exchanges, and 4% overall.

6.3.3 Evaluation to some bio-based products characteristics

Bio-based materials, as indicated earlier, have been used historically for their performances. As an example, reed presents these relevant properties:

(a) It has good resistance to water actions.
(b) It is durable and flexible in technical action and structures, since it contains a high ratio of silicon substance.
(c) It is an efficient insulator.
(d) It is also a low-cost material, is less labour-intensive and requires less skills if compared with other traditional construction materials (Carneiro *et al.*, 2016).

However, reed is flammable, and its natural durability is lower than some other bio-based materials. Therefore, it must be protected from fire and from biodeterioration, eventually treated with preservatives, for safety reasons and to prolong service life (Almusaed and Almssad, 2015). One possibility for its use can be the integration of reeds and reed fibres on earth-based monolithic walls, by a technique similar to vernacular cob but low labour-intensive compared with other earth-based wall-building techniques (Faria *et al.*, 2016) (Fig. 6.6).

Fig. 6.6 Easy to build monolithic wall made of layers of earth and reed-fibre mortar and layers of reed, with simple framework (just to define vertical alignment) and wood pillars.

Thermal properties of reed-insulated walls were studied in a dedicated test house by Miljan *et al.* (2014). Thermal transmittance measurements through heat-flow plates showed how the wall insulated with compressed loose reed placed horizontally met Estonian legislative requirements.

The wide availability of reed (an invasive species) makes the material very attractive for green buildings' applications. Increase of fire resistance can be achieved if reed-based materials are installed within internal partitions gaps, between gypsum-based panels, for instance. Its fire-resistance capability is enforced by the gypsum layers and could be considered similar to the one obtained by kenaf- and sheep-wool-based materials already commercialised for the same extent and tested according to EN 13501-1/A1 (CEN, 2007/2009), as specified by Asdrubali *et al.* (2015). Besides this, the durability performance is not compromised by indoor applications. In the future, possible application for external partitions may be investigated by a mineralisation procedure of common reed-based material, according to Asdrubali *et al.* (2015).

Palumbo *et al.* (2015a) gathered data of different renewable crop by-products that indicate that the amount is sufficient to meet estimated demand of thermal insulation in Spain, being enough to insulate 250,000–450,000 dwelling per year. Materials ranged from cereal straw (pellets or bales), hemp boards, wood-based boards, coconut boards, flax boards, to corkboards or granular cellulose present densities of 36–172 kg/m^3, with an overall average of 99 kg/m^3, and thermal conductivity of 0.039–0.055 W/(m K) with an overall average of 0.045 W/(m K). Palumbo *et al.* (2015b) compared fire behaviour of thermal-insulation boards developed from renewable food crop by-products (rice husk, corn pith and barley straw) and binders (starch and alginate). All the natural boards performed better than of polystyrene and polyurethane. The bio-based insulation boards had 71.4%–97.1% of vegetal fibres (28.6%–2.9% natural binder) and density of 50–223 kg/m^3. For application in buildings, these boards with low embodied energy will be very positive for the life-cycle assessment (*LCA*) of the buildings whilst contributing to solve waste management aspects.

Wood is a well-known natural-building material, but technical properties are highly dependent on the type and moisture content. Timber is generally recognised as a thermal insulator, but with the increase of insulation thickness, the timber components may represent zones of slight heat loss, since its thermal conductivity is fractionally higher than insulation materials (Qasass *et al.*, 2014). However, the heat loss is significantly lower than other conventional-building materials (stone, concrete, steel, etc.).

Stazi *et al.* (2014) compared the effect on energy consumptions, comfort levels, environmental sustainability of two different wood-based innovative building envelopes, that is, wood-cement and massive wood, with a masonry structure. Those two energy-efficient envelopes were recently introduced in the European Mediterranean area and are characterised by different thermal inertia. In order to achieve this goal, a multidisciplinary approach was adopted involving: the study of the energy performance in winter and summer using analytical models both in semistationary and dynamic conditions. The three envelopes' performance were analysed through a multidisciplinary approach involving analytical models both in semistationary and dynamic conditions, analysis of thermal bridges, analysis of annual comfort and LCA analysis. The research work showed that a wood-cement envelope is more effective in winter, whilst the wood envelope presents both a low cost and environmental low impact. Besides this, the adoption of a wood lightweight envelope, even if not convenient with regard to comfort aspects for the risk of overheating, it is preferable for its lower exploitation of environmental resources and economic convenience. Nevertheless, to enhance its summer behaviour, passive-cooling techniques (such as the introduction of inner massive finishing or night-time ventilation) may be adopted.

Ber *et al.* (2014), instead, investigated the thermal-energy performance of a load-bearing composite timber-glass panel for glazing wall applications, with varying the connection system between the two materials. They found that such innovative wall element can contribute to efficiency of buildings by increasing solar gains. Pinto *et al.* (2011, 2012) found that similarities exist between corn cob and expanded polystyrene (*EPS*) regarding their microstructure. However, the corn-cob panels developed by the authors presented a higher thermal conductivity than EPS. Similar results were also obtained previously by Dowling and Mathias (2007). Wang and Sun (2002) tested low-density boards with a mixture of wheat straw and corn pith with promising properties. De Long (1923) developed light composites using lime/metakaolin and sunflower pith, to be used for instance in walls as self-bearing blocks with improved insulation properties. Krus *et al.* (2014) developed cattail-leaf-based insulation boards with bulk density of 220–350 kg/m^3 and a thermal conductivity of about 0.055 W/(m K).

Brás *et al.* (2013) and Brás and Gomes (2015) presented works regarding the use of cork in vertical opaque envelopes of existing buildings, especially for thermal-bridge correction. Ordinary cement and hydraulic lime mortars where compared with cork-added and EPS-added similar mortars. Energy performance and energy audit of the building was estimated and compared with the original behaviour of a school building. LCA (cradle-to-gate) was used to compare the environmental impacts of building thermal rehabilitation and its effect on the energy consumption for heating and operational energy (*OE*), for different mortars service life. A simulation made in the school building shows that ordinary cement or hydraulic lime mortars, leads to much higher global warming potential, where CO_2 emissions are more than 3 t per building intervention. The use of mortars with cork addition, leads to a reduction of CO_2 emission up to 30% and 20% reduction in embodied energy (*EE*), when compared with traditional mortars, because cork mortars presents smaller EE than EPS mortars.

Table 6.1 summarises some major added values of bio-based boards applied for energy efficiency of buildings, in comparison with common polystyrenes (EPS and *XPS*)

Table 6.1 Characteristics of bio-based boards in comparison with polystyrenes (Asdrubali et al., 2015; Korjenic et al., 2016)

General physical characteristics	EPS	XPS	Wood fibre	Cork	Reed-based	Hemp	Flax	Jute	Bio-based PCM
Density (kg/m^3)	20–50	30–55	180	65–200		30–110	32.1	26	750 (liquid)–820 (solid)
Typical thicknesses (mm)	20–200	30–160	10–160	2–12		10–80	11	95	0.2 (liquid)–0.12 (solid)
Thermal conductivity (W/(m K))	0.029–0.041	0.025– 0.035	0.038– 0.041	0.037– 0.050	0.045–0.055	0.062	0.065	0.058	
Acoustic performance (–)	Poor	Poor	Good	Good		0.15–0.55	0.4	0.4	
Water vapour diffusion resistance factor, *m*-value (–)	25–200	80–200	5–10	5–10		2.2–4.2	2.9	2.1	
Fire classification (–) (EN 13501-1:2007)	B1–B2	B1–B2	E	E					
Temperature application range (°C)	−80 to 80	−60 to 75	N.A.	N.A.					

6.3.4 Prioritisation and choice of measures

The nature and extent of bioeconomy challenges requires widespread collaboration among several players like industry, research institutes and universities. This is crucial for the stimulation and growth of strong research and innovation environments, accelerating development, verification and commercialisation of new bio-based solutions, and to provide continued support for the demonstration of products, systems and services other than fuels and energy technology solutions.

A bio-based economy cannot be achieved until the materials and products developed are sold on the market. The goods and products that are introduced must be as good as, or more attractive than, those they are intended to replace. The challenge here, in addition to offering attractive and competitive products, is also to achieve consumer awareness and a desire to contribute to switching to a bioeconomy, for example, by influencing purchasing habits. New services, in combination with bio-based products, can also contribute to generating added value in a bioeconomy.

6.4 Indoor air quality

B. Stefanowski, S. Curling*, G.A. Ormondroyd*,†*
*Bangor University, Bangor, United Kingdom
†University of Bath, Bath, United Kingdom

6.4.1 Indoor air pollution

In an attempt to combat climate change, the European Commission developed an EU climate action plan, with key targets to cut greenhouse gas (*GHG*) emissions by 40% and increase energy efficiency by 27% by 2030 (EC, 2016). New legislation such as the Climate Change Act 2008, Energy Bill 2012 and the Building Regulations and associated technical guidance (Shrubsole *et al.*, 2014) has been implemented, targeting GHG emission reductions in the building sector. Such new legislation, policies and incentives have generated a greater push for retrofitting old and new dwellings and public buildings in order to increase airtightness and energy efficiency (Knudsen *et al.*, 2002; Shrubsole *et al.*, 2014; Spengler and Sexton, 1983; Weschler, 2004; Yu and Kim, 2010). It has been noted that total pollutant concentrations are heightened as a consequence of increased building tightness, resulting from reducing air exchange (Allen *et al.*, 2016; Takagaki *et al.*, 2000). According to the US Environmental Protection Agency (EPA), indoor air can be two to five times more polluted than outdoor air (Allen *et al.*, 2016; Wolkoff *et al.*, 1997; Yrieix *et al.*, 2010). It has been shown that the mean concentration of individual compounds in established buildings is generally below 50 $\mu g/m^3$, whilst total compound concentrations are substantially higher, for example, 1100 $\mu g/m^3$ (Brown *et al.*, 1994). It is this build-up of total chemical compound emissions that is now recognised as a potential hazard to human health (Yu and Kim, 2010) even if they are considered relatively chemically inert (Wolkoff *et al.*, 1997). The scientific understanding of indoor air quality has

increased in the past few decades, with much of the previous work focused on particulates, outdoor pollution penetrating inside buildings (WHO, 2010) and chemicals (Mitchell *et al.*, 2007). More recently, research has begun to involve the relationship between the building environment, its occupant's activities and the different sources of pollutants. Although indoor air pollution takes many forms and is ubiquitous, the types of pollution vary around the world. In developing countries, smoke, gases and particulate matter from the combustion of solid fuels such as coal (Zhang and Smith, 2003) are the most common pollutants of indoor air and might be responsible for 1.6 million deaths a year (WHO, 2010). In more modern countries and buildings, pollution is caused by a complex mix of volatile organic compounds (*VOCs*). According to the EC Directive 999/13/EC (Solvent Emissions Directive), VOCs are compounds having a vapour pressure of 0.01 kPa or more at 293.15 K (20°C) or having a corresponding volatility under particular conditions of use. However, other EU Directives have different definitions for VOC. EU Directive 2004/42/EC defines a VOC as an organic compound having an initial boiling point lower than or equal to 250°C at an atmospheric pressure of 101.3 kPa, and the EU 2001/81/EC Directive defines a VOCs as any organic compound of anthropogenic nature other than methane that is capable of producing oxidants by reaction with nitrogen oxides, in the presence of sunlight. A VOC is any compound with a boiling point between 50 and 100°C and between 240 and 260°C, corresponding to having saturation vapour pressures at 25°C greater than 100 kPa. These VOCs include alkanes, alcohols, branched cycloalkanes, halogenated compounds, ketones, aldehydes, esters, aromatic hydrocarbons and terpenes (Brown *et al.*, 1994). Most of these compounds can be categorised into volatile aromatic hydrocarbons (*VAHs*), volatile aldehydes (*VAs*) and semivolatile compounds (*SVOCs*) (Yu and Kim, 2010). Often, these VOCs are grouped for simplicity as total VOCs (*TVOC*), and the total quantity and composition of emissions vary with the type of building and its primary use. With increased understanding and information regarding VOCs and indoor air quality, there has been an increase in the level of concern regarding indoor pollution and human health, as most people spend between 70% and 80% of their time indoors (Brown *et al.*, 1994; Yrieix *et al.*, 2010), and the proportion of emissions that are inhaled is greater when emissions occur indoors than outdoors (Nazaroff and Weschler, 2004).

Brown *et al.* (1994) pooled data from literature from a number of different countries and found that dwellings have higher TVOC concentrations than in established public buildings.

There are government initiatives in place to target this build-up of indoor pollution. In European countries such as Germany, Finland and France, there are environmental schemes in place to provide criteria for control of building environment quality and include certification limits for emissions from building materials (Yu and Kim, 2010). The UK government developed a series, the Building Regulations 2010 approved documents, which addressed a number of issues and incorporated performance criteria for dwellings and other buildings to provide adequate building structure, ventilation, fire safety, resistance to contaminants and moisture to aid in the prevention of the build-up of indoor pollutants to levels that could be harmful to human health (Yu and Kim, 2010).

There are a great number of sources of both VOCs and formaldehyde, with those occurring naturally known as biogenic emissions; for example, vegetation is known to release alcohols, aldehydes and ketones (Roffael, 2006). Natural sources of formaldehyde are varied, for example, meat (2–20 mg/kg), fruit and vegetables (6.3–35 mg/kg) (Trézl *et al.*, 1997) wood (0.04 mg/kg) (Meyer and Boehme, 1997) with even volcanoes known to release it (WHO, 2010). Formaldehyde is also a product of human metabolism and can be detected in human breath at levels ranging from 1.2 to 72 ppb (Moser *et al.*, 2005). Other sources of formaldehyde include: furniture, paints, varnishes, textiles, wallpapers, glues, detergents, disinfectants, shampoos, electronic equipment and cosmetics (WHO, 2010). VOCs have also been reported to be emitted from solvent thinners, degreasers, cleaners, lubricants and liquid fuels (Ghoshal and Manjare, 2002; Nazaroff and Weschler, 2004), as well as construction materials such as gypsum board, medium-density fibreboard (*MDF*), solid wood, orientated strand board (*OSB*), flooring, carpets, tables, chairs and even cements (Brown *et al.*, 1994; Kim, 2010; Makowski and Ohlmeyer, 2005; Ohlmeyer *et al.*, 2008; Yu and Kim, 2011). It must be noted that only a proportion of VOCs found in products such as cleaning agents, are considered a direct hazard to human health (Nazaroff and Weschler, 2004; Schripp *et al.*, 2012). Common types of VOCs include benzene, toluene, cyclohexane, ethylbenzene, *m*- or *p*-xylene, *n*-nonane and naphthalene (Reitzig *et al.*, 1998; Wolkoff *et al.*, 1997), and less common include dimethyl phthalate (*DMP*), camphene, *o*-xylene and C_{12}-alkene. Many of these VOCs are malodorous and do not go unnoticed by occupants. Other potential sources of emissions include interior furnishing, cleanings agents, cigarettes (Niedermayer *et al.*, 2013) thermal and acoustic insulation materials commonly used to line the interior of ventilation systems and ducts (Haghighat and De Bellis, 1998). Outdoor air pollutants are also often found in the indoor environment and in higher concentrations than outdoors (Brown *et al.*, 1994).

6.4.2 Primary pollutants

Indoor air pollutants can be categorised according to their source, either primary or secondary. Primary sources range from fuel combustion from cooking, heating, smoking to synthetic materials, chemicals from various products and building products (Mitchell *et al.*, 2007; Spengler and Sexton, 1983). Primary emissions are a result of several mass-transport processes (Haghighat and De Bellis, 1998), and whilst the effects on material emissions are complex, two main processes can be considered. The first is diffusion within the material, which can be a result of concentration, partial pressures, temperature and density gradients, all of which can vary with the product type, composition and other properties such as porosity, capillary structure and thickness (Hun *et al.*, 2010; Ohlmeyer *et al.*, 2008). Each compound has its own diffusion coefficient dependent upon its molecular weight, molecular volume and temperature and the materials' characteristics (Haghighat and De Bellis, 1998). VOCs that have low molecular weight will quickly decay and emit rapidly from their source and will escape the confines of a building within weeks or months (Markowicz and Larsson, 2014) Such VOCs are unbound to the materials. Others are slow-decaying emissions by processes such as aging and degradation of a material, for example, hydrolysis,

sorption processes and are typically chemically bound between an absorbent and adsorbate or can be physically bound by van der Waals or electrostatic forces (Markowicz and Larsson, 2014). These slow-decaying VOCs last for longer periods of time inside buildings, as they are less reactive (Markowicz and Larsson, 2014).

The second emission process is via the materials' surface (Wolkoff *et al.*, 1997), and as for a given air volume, there are far more surfaces indoors than outdoors, surface reactions must influence chemical composition in indoor air to a greater extent than compared with outdoors (Weschler, 2004). Reactions occurring between a materials surface and the surrounding air are influenced by mechanisms such as convection and evaporation (Hun *et al.*, 2010), with emissions occurring wherever there is a gradient between the two. The amount of emissions is influenced by surface energies and characteristics and properties of the air such as surface velocity and turbulence (Haghighat and De Bellis, 1998). It has been considered that reactions with indoor surfaces contribute to indoor pollution just as much as reactions in the gas phase (Weschler, 2004).

6.4.3 Biological pollutants

Microbiological pollution includes hundreds of species of bacteria, fungi, moulds and mites that can contribute to poor indoor air quality (WHO, 2009). Fungi are known to release a range of metabolites, some of which (termed mycotoxins) are known to cause adverse health effects (Abbott, 2002). It has been shown that mycotoxin production by indoor moulds occurs most significantly at high moisture contents of the substrate (Nielsen, 2003; Viegas *et al.*, 2015). In nature, these mycotoxins are the chemical defences for the fungi against other microorganisms and herbivores (Abbott, 2002). These mycotoxins can however pose as a hazard to human health (Jarvis and Miller, 2004; Viegas *et al.*, 2015), contributing to allergies, respiratory conditions and can act as immunosuppressants (Jarvis and Miller, 2004; Nielsen, 2003; WHO, 2009). Mycotoxin producing moulds, such as *Aspergillus, Penicillium* and *Chaetomium*, are very common in the indoor environment (Nielsen, 2003; WHO, 2009), and the type, composition and quantity of mycotoxins produced are fungal-species-specific (Viegas *et al.*, 2015). For example, *Aspergillus* mould species have a huge array of mycotoxins such as gliotoxins, fumitoxis and verruculogen (Nielsen, 2003). *Chaetomium globosum* is the most common of *Chaetomium* moulds and produces cytotoxic chaetomins capable of inhibiting cell division (Nielsen, 2003). These fungal mycotoxins, fungal spores, mycelium and hyphae fragments can be found practically anywhere indoors, and some are allergen agents that elicit an immune response.

Fungi also produce VOCs, specific to genera and individual species (WHO, 2009) such as aldehydes, terpenes and ketones that are similar to the VOCs commonly released from other sources indoors (WHO, 2009). Emissions are a result of a combination of moisture and chemicals for adsorption sites of mouldy materials; hence, at higher RH, mould emissions increase (WHO, 2009).

Bacteria found within indoor environments are also considered indoor contaminants, and whilst the vast majority of bacteria that could be brought in from outdoors or found on humans are considered generally harmless, some bacteria that can actively grow on indoor substrates can be hazardous to human health (WHO, 2009). Water is a

critical requirement for bacteria, more so than fungal growth (WHO, 2009). Bacterial species such as streptomycetes produce a range of toxins, and mycobacteria cell wall components are known as immunogenics, and exposure to them can cause inflammatory responses (WHO, 2009).

6.4.4 Secondary pollutants

Secondary pollutants are those that occur as a result of chemical reactions between primary pollutants (Patkó *et al.*, 2013; Weschler, 2004), pollutants from outdoors, ozone (O_3) or UV light (Kim, 2010; Knudsen *et al.*, 2002; Wolkoff *et al.*, 1997). For example, oxidations of VOCs often result in the formation of formaldehyde (WHO, 2010) and cleaning products that contain VOCs react with unsaturated organic compounds, producing secondary pollutants (Nazaroff and Weschler, 2004). Such chemical reactions are a major factor in the composition and concentration of indoor air pollution (Weschler, 2004). Often, these reactions are a major source of VOCs that are short-lived and highly reactive (Weschler, 2004). It is these VOCs that add further complication in predicting future indoor air pollution.

Ozone (O_3) present inside buildings can be emitted from items such as photocopiers and printers, but it is largely present from the outdoor environment (Schripp *et al.*, 2012). It is a strong oxidising agent (Zhang and Smith, 2003) and can react freely with unsaturated chemical VOCs in indoor air (Knudsen *et al.*, 2002), it is highly reactive with indoor material surfaces (Knudsen *et al.*, 2002; Schripp *et al.*, 2012) and readily oxidises terpenes naturally occurring in the air (Nazaroff and Weschler, 2004; Roffael, 2006; Schripp *et al.*, 2012; Weschler, 2004) and often results in hydroxyl radicals (Weschler, 2004). O_3 oxidation of C–C double bonds also results in simple aldehydes, including formaldehyde (Hun *et al.*, 2010; Roffael, 2006; WHO, 2010; Wolkoff *et al.*, 1997). It has been found that reactions between ozone and styrene and between limonene and ozone can produce up to 500 $\mu g/m^3$ of formaldehyde (Conner, 1996). Ozone reactions are thought to dominate indoor chemistry, and hence, ozone is found in comparatively low concentrations indoors. However, some of these reactions can result in the formation of ultrafine particles (Hodgson *et al.*, 2002) that can have adverse human health affects (Schripp *et al.*, 2012) and form hydroxyl radicals (OH) and nitrate radical (NO_3) (Weschler, 2004). These radicals can then result in further chemical reactions with most organic compounds found in indoor air (Nazaroff and Weschler, 2004; Weschler, 2004). However, there are some discrepancies in some studies, due to the complexity of the topic. It has been shown that ozone will react with some compounds, but it has also been shown not to react with other VOCs such as limonene (Knudsen *et al.*, 2002).

Hydrolysis reactions are another example resulting in secondary pollutants. Hydrolysis that occurs on material surfaces are a result of the surface being moist, that is, damp building materials (Weschler, 2004). This is a problem when it comes to esters, which are susceptible to hydrolysis. Esters are present in the room as they are used in various products such as insecticides and pesticides. Dampness in buildings is suspected of facilitating hydrolysis of esters, thus contributing to health problems associated with damp buildings (Weschler, 2004). Hydrolysis also results in aldehyde

emissions, namely, formaldehyde from different surfaces (Hun *et al.*, 2010). However, it is often hard to singularly describe a VOC as a primary emission or secondary emission. Formaldehyde, for example, is naturally ubiquitous in the atmosphere and can be not only generated through many chemical pathways but also released from synthetic products (Roffael, 2006).

6.4.5 Environmental parameters

There have been many studies that show that indoor environmental parameters influence a materials' emissions rate and, subsequently, therefore, indoor air quality (Kim, 2010). The two main parameters that affect emissions are temperature and RH. The absorption and desorption mechanisms between VOC and material surface can be influenced by temperature and RH as well as their physical and chemical properties (Markowicz and Larsson, 2014; Nazaroff and Weschler, 2004). Therefore, studies have been conducted investigating single materials' emissions at different temperature, RH and ventilation.

6.4.5.1 Temperature

With increased temperature emission rates tend to increase as elevated temperatures generally increase the rate at which indoor and material surface reactions occur, although there are some exceptions (Weschler, 2004; Wolkoff *et al.,* 1997) It has been found that even from solid wood an increase in temperature results in more formaldehyde being liberated from the starch and lignin components (Salem and Böhm, 2013; Schäfer and Roffael, 2000). An increase in temperature from 23°C to 40°C increased formaldehyde emission rates over five times from particle boards (Pacheco-Torgal *et al.*, 2012). Andersen *et al.* (1975) also reported similar findings and formaldehyde emission rates from chipboard doubled for every 7°C temperature rise between 14°C and 31°C. Xiong and Zhang (2010) evaluated the formaldehyde emissions from MDF. They noted that, at room temperature, the MDF panels emitted far below the limit set by European standards but, as temperatures were increased, the increase in formaldehyde emission was exponential. Temperature acts as a catalyst for chemical reactions and, for formaldehyde bound to materials, provides the additional kinetic energy needed to overcome the binding forces (Pacheco-Torgal *et al.*, 2012). However, this type of formaldehyde emission is smaller than free formaldehyde emissions and emissions resulting from hydrolysis reactions (Pacheco-Torgal *et al.*, 2012).

Temperature fluctuations alters the VOC profile observed as with higher temperatures, less volatile compounds such as diterpene can be emitted (Hun *et al.*, 2010; Roffael, 2006). This is important when considering when to take samples from an environment as at lower temperatures, some of these VOCs would not be detected. However, not all VOCs are affected by temperature increases (Pacheco-Torgal *et al.*, 2012). Haghighat and De Bellis (1998) conducted an experiment evaluating the VOC emissions from paints and varnishes, which revealed that with increasing temperature the TVOC emissions rates increased; however, individual compounds did not always follow the same trend, with some showing higher emission rates at lower temperatures.

6.4.5.2 Relative humidity

The studies of the influence of RH on VOC emissions are more complicated than for temperature however. Studies such as that conducted by Markowicz and Larsson (2014) and van Netten *et al.* (1989) have found that increased RH does increase emissions of formaldehyde, likely due to the fact that formaldehyde is highly hydrophilic and an increase in air moisture increases rates of hydrolysis. Andersen *et al.* (1975) reported that when chipboard is exposed to 30% RH and then to 70% RH the formaldehyde emissions double.

Although it is still true that hydrolysis of VOCs does increase emissions, it is VOC-specific. It has also been noted that, despite increased emissions of formaldehyde from materials, the diffusion coefficient shows little change despite the increased RH (Pacheco-Torgal *et al.*, 2012). As water is polar and based on the 'like-for-like' principle, VOCs susceptible to hydrolysis are also polar compounds (Markowicz and Larsson, 2014). Therefore, some non-polar organic compounds, for example, toluene behaves differently to increase RH, with release rates not increasing with RH. However, changes in RH can impact VOC emissions in unsuspected ways. Haghighat and De Bellis (1998) found that emissions from painted surfaces, at the same temperature and different RH, increased at 35% RH but decreased again at 62% RH. This highlights that different VOCs from different sources will respond to environmental conditions uniquely and specifically to the material and VOC relationship, with some increasing emissions concentration, rates or negligible changes (Pacheco-Torgal *et al.*, 2012). For example, Fang *et al.* (1999) experimented on TVOC emissions from building materials at 30%, 50% and 70% RH. The results obtained showed that TVOC emissions from floor varnish and wall paints correlated with increasing RH; however, TVOC emissions from carpet and PVC flooring showed a negligible change in emissions. To add to the complexity, RH has also been shown to affect secondary emissions in the indoor environment, namely, through hydrolysis reactions and result in such VOCs as ammonia and butanol from flooring (Kim, 2010).

6.4.5.3 Ventilation

Unsurprisingly, a lower ventilation rate increases concentrations of formaldehyde and VOCs (Conner, 1996; Nazaroff and Weschler, 2004). Low ventilation rates increase the accumulation of VOCs and formaldehyde in a building or in a single room. Without adequate ventilation, gas-phase reaction chemistry is promoted, and therefore, an increase in secondary pollutants occurs (Weschler, 2004). However, a reduced concentration in VOCs increases the difference in vapour pressures between the VOC source and the indoor atmosphere, and this vapour difference drives evaporation from the VOC source and therefore increases its emission rates. However, in turn, as diffusion plays a key role in emissions from a material, if diffusion of a volatile compound to a materials' surface is slower than the rate of evaporation, then the overall emission rate is reduced. So, the influence of ventilation and surface interactions and emissions is a very complex one and again can often be VOC-specific. Insulation of a building also influences indoor air quality and not in the least because it increases building tightness and reduces air exchange.

Different types of insulation emit their own VOCs and formaldehyde. A heavily insulated building will also increase average house temperatures and RH, thereby increasing the impact of them on emissions. This is especially true during summer periods and can result in overheating of a building, especially in top floors of high-rise buildings (Shrubsole, 2015).

6.4.6 Other parameters

6.4.6.1 Building occupants

Another major influence on indoor air is the building occupant's daily activities, work routine, preferences to particular products and their frequency of use such as cleaning, candles, smoking or cooking with gas or oil. The presence of pets can also affect air quality. Human occupants can also generate spatial variations of pollutants in different rooms as some are used more than others, are used for different purposes, and contain different, localised sources of VOCs (Nazaroff and Weschler, 2004).

6.4.6.2 VOC characteristics

The characteristics of individual or groups of VOCs will also influence indoor air quality. An example is glycol ester, which is released from aqueous cleaning products slowly over hours if not days after its application (Nazaroff and Weschler, 2004). Other VOCs, as mentioned before, can be more or less susceptible to environmental conditions and have different chemical reaction capabilities. VOCs of a low or moderate vapour pressure or high polarity may bind onto materials surfaces or into the bulk of a material, reducing peaks in concentrations of pollutants in an indoor environment (Nazaroff and Weschler, 2004). Some materials can also absorb VOCs released from other materials and desorb them at a later time (Haghighat and De Bellis, 1998; Markowicz and Larsson, 2014; Niedermayer *et al.*, 2013) creating a buffering of pollutants.

6.4.6.3 Air velocity

One other final, environmental parameter that influences emissions is the air velocity across the surface of a material. This can occur on smaller scales, such as disturbances by an occupants' movement through a room or by drafts and open windows. The air velocity across the surface of a material will affect, what is called the convection mass transfer coefficient (h_m) of VOCs (Pacheco-Torgal *et al.*, 2012). A higher air velocity can decrease the layer of still air adjacent to the material surface, increasing h_m and increase emissions from that material (Pacheco-Torgal *et al.*, 2012). This affect is also influenced by the diffusion capabilities of the VOC in question, if diffusion is greater, then the influence of air velocity will be negligible (Pacheco-Torgal *et al.*, 2012). It has also been stated that, VOC emission rates from construction materials, is only temporarily influenced by air velocity, during the first few days after production to any great extent (Wolkoff, 1999).

6.4.7 Sampling and analysis of VOCs

Due to the growing concern of the adverse effects of indoor pollution from formaldehyde and VOCs on human health, legislation and guidelines values have sparked an increase in research into this field of science. Since the problem of indoor air pollution was first addressed in the 1970s, there has been a vast quantity of scientific research across the world, but not without its problems and areas of bias. This section briefly highlights some of the problems faced when sampling and analysing indoor air and VOCs.

There is naturally a vast amount of VOCs, and it is impractical to study each individual compound and develop an emissions profile for all of them. Therefore, specific compounds such as formaldehyde are targeted or a material emissions or a total VOC (TVOC) concentration is recorded. However, when comparing studies, this can become somewhat problematic as the results and analysed observations made are limited by the equipment, sampling techniques used, spatial and temporal variations and environmental factors (Markowicz and Larsson, 2014; Wolkoff *et al.*, 1997). Taking air samples within buildings of TVOCs can also be influenced by particular compounds found in much higher concentrations than others and can mask true emission mechanisms taking place (Haghighat and De Bellis, 1998). Temporal and spatial variations can also affect TVOC measures as materials may buffer VOCs by temporarily absorbing compounds and desorbing them at a later time (Haghighat and De Bellis, 1998; Markowicz and Larsson, 2014; Niedermayer *et al.*, 2013). Materials such as nylon and olefin-fibre carpets will absorb more non-polar compounds, whilst materials such as gypsum board absorb polar compounds (Hun *et al.*, 2010; Markowicz and Larsson, 2014). The air-sampling location is very important, it is not always suitable to take an air sample or reading from the centre of a room as there could be localised emissions from particular materials (Nazaroff and Weschler, 2004), and therefore, the TVOC reading is not truly representative of a real-life scenario. The air-sampling period is also important, as some VOC concentrations can be time dependant (Brown *et al.*, 1994), for example, if the occupants are cooking or the position of the sun relative to the window. There could also be 'interzonal' transport of VOCs in buildings, due to ventilation, drafts and occupant movements, whereby the VOC in question could be brought in from elsewhere and increasing exposure that would otherwise go unexposed (Nazaroff and Weschler, 2004). Another problem is that TVOC samplings also incorporate natural VOCs some of which are harmless and unless the TVOCs are broken down into their individual compounds, the term TVOCs can be misleading for studies considering the impacts on human health (Kim, 2010). All the abovementioned can cause readings of VOCs to be false or only tell part of the story.

Environmental chambers are a good technique for determining TVOC concentrations and were first introduced in the 1980s and have now been standardised in Europe in ISO 16000 (Kim *et al.*, 2007). However, the main limitation of these is mainly their cost and time consumption (Kim *et al.*, 2007). Other in situ techniques include differential optical absorption spectroscopy (*DOAS*), Field and Laboratory Emission Cell (*FLEC*), Fourier transform infrared absorption (*FTIR*) and laser-induced fluorescence spectroscopy (*LIFS*). The FLEC method is a popular method due to its high sensitivity and has also become part of a standardised method ISO 16000 in Europe (Kim *et al.*, 2007).

These test methods have a number of benefits, but they are costly, and the sensitivity is strongly affected by RH and therefore not always suitable for routine tests (Salthammer *et al.*, 2010). When comparing such in situ studies, one has to ensure that certain aspects have been addressed as so many internal (material type, age and composition) and external (ventilation, temperature, RH and time) factors can influence TVOC measurements, and all of these factors can be influenced by the building itself and its primary purpose, be it school, domestic or public (Brown *et al.*, 1994). For true comparisons of a buildings total emissions, all these factors should be the sample, and this is of course can be hard to achieve.

There are also limitations with other analytical equipment such as gas chromatography–mass spectrometry (*GC–MS*). This is a common method used to identify if particular VOCs are present rather than just determining TVOC. However, this equipment also has its limitation. Besides being costly, it also limited by its internal library of compounds. There can also be some subjective error, as the GC–MS can reveal significant number of peaks, and some at lower peak areas may be rejected from the final analysis or masked by more concentrated compounds (Kim *et al.*, 2007). This creates a level of uncertainty when analysing GC–MS results (Yrieix *et al.*, 2010). Other compounds that have particularly high reactivity may not be sampled or may be destroyed during the analysis procedure (Weschler, 2004). There are a number of compounds that are undetectable with modern equipment and analytical equipment or are decomposed, for example, when exposed to high temperatures in a chromatographic column or are short-lived (Weschler, 2004). Indeed, modern sampling methods and specific environments can mean that some compounds are never detected unless analysis with specialised equipment and specific regimes. However, there has been significant research conducted looking at specific materials and products.

6.4.8 Reducing emissions

Work on assessing the health effects of poor indoor air quality has lagged behind the assessment of outdoor pollution for several reasons. The main reason is that outdoor pollution has severe levels of pollution from coal smoke and photochemical smog, and it is more feasible to monitor outdoor pollution on a large enough scale to develop standards and regulations (WHO, 2010). Assessing the human-health risks of indoor air pollution is quite difficult and far more complicated due to the multitudinal sources of pollutants and the types of pollutants, chemicals, particles and biological materials, and how they interact with their environment. However, despite this, there has been some significant research studies and regulations developed to combat the issue of poor indoor air quality. The reduction of emissions can be tackled at four different levels: occupants, architects and developers, manufactures and government.

6.4.8.1 Occupants

Individual occupants of dwellings can ensure they use and maintain products correctly, reduce the use of products that release VOCs such as candles and properly use solvents, cleaners, varnishes, herbicides and pesticides (Spengler and Sexton, 1983).

6.4.8.2 Architects and developers

Architects and developers should consider indoor air quality in building design and consider appropriate ventilation systems for the building in question. Adequate ventilation appropriate to the building design can significantly reduce the concentration of VOCs to harmless levels (Kim *et al.*, 2006) by creating air exchange to dilute and remove pollutants. Ventilation helps to maintain indoor RH at a level that restricts microbiological activity and thus reduce emissions of fungal VOCs and mycotoxins that have shown to increase with increasing moisture content of a substrate (Nielsen, 2003; Viegas *et al.*, 2015). Ventilation can be classed as natural, mechanical or a combination of both and the correct system must be applied specifically to the design of the building. An incorrect ventilation system can in itself aid indoor pollution and have adverse effect on human health (WHO, 2009). However, ventilation systems need to be suitably designed and correctly installed to the building it is intended for and adequately maintained and used.

Substitute products can be used in place of VOC emitting products. Developers can use natural substances such as turpentine oils as substitutes for conventional solvents and alternative paints (odourless paints) and glues that contain fewer compounds that would otherwise be emitted into the indoor environment (Reitzig *et al.*, 1998). Developers should try to eliminate, contain or reduce high emitting materials wherever possible (Spengler and Sexton, 1983).

Architects and developers should also consider using other materials that can be multifunctional and actively absorb formaldehyde and VOCs from in the indoor environment. Niedermayer *et al.* (2013) conducted an experiment on 25 different materials currently used in construction and found that MDF, particle board, three-layer boards, gypsum, plasterboards, sealants and insulation materials will absorb indoor air pollutants. Some with high adsorption capacities will bind substances strongly and are less likely to desorb them. The study showed that MDF panels had the strongest absorption of pollutants and showed the lowest released of absorbed VOCs.

6.4.8.3 Manufacturers

Manufacturers of products and materials should test, certify and label products that are potential sources of air pollutants and, where possible, conduct research into alternative compositions and methods of production (Spengler and Sexton, 1983).

Even with extensive efforts to reduce formaldehyde emissions, formaldehyde will always be present in the indoor environments, simply because it is emitted from natural materials such as wood. Therefore, ‘zero-emission’ wood-based panels are not achievable (Meyer and Boehme, 1997; Roffael, 2006; Weigl *et al.*, 2009). But there are simple measures to reduce natural emissions of formaldehyde and VOCs such as drying and storing the wood for longer periods of time before processing (Roffael, 2006; Salem and Böhm, 2013). Surface treatments of construction panels such as placing a coating on top such as lacquer, paints and laminate surfaces can reduce emissions (Hun *et al.*, 2010; Schripp *et al.*, 2012). Research studies have found that veneers and vinyl are very effective as barriers for formaldehyde and other aldehyde emissions (Hodgson *et al.*, 2002; Salem *et al.*, 2012; Salem and Böhm, 2013). However, this can in the long-term cause additional emissions as the glues and solvents or non-cured

components age and emit VOCs (Schripp *et al.*, 2012). This has led to the development of 'green' lacquers and natural paints. Composition of panels makes a difference to emission quantities too; for example, particle board made with higher proportions of beech has lower formaldehyde emissions than those consisting of more pine particles (Salem and Böhm, 2013). The most common method of reducing emissions from construction products is to replace formaldehyde resins with alternatives such as isocyanate-based adhesives. These include methylene diphenyl diisocyanate (*MDI*), polymeric MDI (*pMDI*), toluene diisocyanate (*TDI*) and hexamethylene diisocyanate (*HDI*). Other chemicals include urea, ammonia and peroxides (Boran *et al.*, 2012). Another method is to reduce molar ratios, that is, reduce the amount of formaldehyde quantities within the adhesive (Myers, 1984; Park *et al.*, 2006).

It is very difficult to eliminate formaldehyde and VOCs from a building completely, from either products or natural materials (Salem and Böhm, 2013). Therefore, more recently, scientific research has been conducted into the use of other additives, termed 'scavengers' that actively absorb formaldehyde and VOCs from the atmosphere. Often, these scavengers are added to other products such as construction panels during production or directly as part of the resin.

Agricultural wastes have shown some great potential in reducing formaldehyde emissions from construction panels. Tannins extracted from mimosa bark, pine and pecan nut can be used in resin modifications to reduce formaldehyde emissions (Roffael *et al.*, 2000). The use of stone pine (*Pinus pinea*) cones has been studied by Ayrilmis *et al.* (2009) and Buyuksari *et al.* (2010) and found that formaldehyde emissions decreased. Walnut shell, almond shell and peanut shells have shown potential in absorbing formaldehyde and VOCs from the atmosphere (Cao *et al.*, 2014; Kim *et al.*, 2001; Pirayesh *et al.*, 2013; Pirayesh and Khazaeian, 2012; Stefanowski *et al.*, 2015).Wool fibres from different animal species have been shown to have some excellent formaldehyde and VOC absorbing capabilities (Curling *et al.*, 2012; Mansour *et al.*, 2016).

Inorganic materials have also shown potential scavengers. Pozzolanic materials that contain reactive silicates and alumina silicates such as volcanic ash, pumicite and shales have shown the ability to absorb formaldehyde. Pozzolanic materials added to UF resin have shown to decrease the release of free formaldehyde from the final product without influencing other product properties such as strength (Kim, 2009). The study conducted by Kim (2009) revealed that TVOC emissions were lower than other organic additives added to resins. Nanoclays have often been used to modify thermosetting resin for wood-based composites (Lei *et al.*, 2008). Lin *et al.* (2006) looked at the potential of using nano-SiO_2 (silicone dioxide) combined with UF resin to reduce formaldehyde emissions from particle board, plywood and MDF. The results showed that, under the same condition and the same F/U molar ratio, formaldehyde emission decreased, and bonding strength increased with increasing addition of nano-SiO_2. Graphite is a carbon nanomaterial whereby the carbon atoms are bonded in layers by weak van der Waals forces, which has the potential to be an effective absorbent, as the forces are relatively weak it allows a variety of molecules and ions to interlace between the graphite layers and therefore great potential to absorb VOCs (Lee and Kim, 2012). However, the advancement of such technologies relies upon industries and manufacturers willingness to take on such modifications to products and possibly modify productions processes at a cost.

6.4.8.4 Government and organisations

On a larger scale, governments should ensure compliance to building and ventilation regulations, sponsor research, establish mandatory guidelines, code and performance standards of buildings and materials. Governments should also provide adequate information to local governments and advise on public safety, construction materials and practices and available monitoring equipment (Spengler and Sexton, 1983).

The World Health Organization (WHO) published the WHO guidelines for indoor air quality: selected pollutants. This document presents guidelines for nine chemicals (benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, polycyclic aromatic hydrocarbons, radon, trichloroethylene and tetrachloroethylene) commonly present in indoor air that pose a risk to human health (WHO, 2010). However, the guidelines developed have been based on the toxicological and epidemiological data available, but there are other chemical compounds found within the indoor environment that can pose as a risk to human health.

In contrast to focusing on individual compounds, the European Commission published the EU Directive 2008/50/EC on ambient air quality and clean air for Europe. This directive recognises the need to minimise emissions of hazardous pollutants, the effects on human health and the need to revise previous Directives to incorporate the latest in research findings. However, this directive focuses on outdoor air pollution. Table 6.2 lists four EU Directives that do consider VOCs and the need for mitigation procedures.

The European directive 210/31/EU on the energy performance of buildings is particularly important as it outlines the requirements for new, existing and majorly renovated buildings to obtain the Energy Performance Certificate. Most importantly, it includes a list of criteria other than energy efficiency that the building must meet, including indoor climate conditions, indoor air quality and ventilation. The EU Environment and Health Action Plan 2004–2010 was developed with the World Health Organization and considered indoor air quality. It brought about the end of smoking in indoor public spaces, highlighted risks from multitude sources of pollutants affecting air quality

Table 6.2 European Directives

Directive	Title
2010/31/EU	The Energy Performance of Buildings
2004/42/CE	Limitation of Emissions of Volatile Organic Compounds Due to the Use of Organic Solvents in Certain Paints and Varnishes and Vehicle Refinishing Products and Amending Directive 1999/13/EC
2001/81/EC	National Emission Ceilings for Certain Atmospheric Pollutants
1999/13/EC	Limitation of Emissions of *Volatile Organic Compounds* Due to the Use of *Organic* Solvents in Certain Activities and Installations
2004/42/EC	Limitation of Emissions of *Volatile Organic Compounds*
2016/1332/EU	Establishing the Ecological Criteria for the Award of the EU Ecolabel for Furniture (Notified Under Document C (2016) 4778) (Text with EEA Relevance)
94/63/EC	Control of Volatile Organic Compound(*s*) Emissions Resulting from the Storage of Petrol and its Distribution from Terminals to Service Stations

ranging from combustion to furniture to humans and emphasising a call for research on the impact of construction materials on human health.

Some countries have passed laws to control the release of formaldehyde by developing standards for limiting its emissions from wood-based products, a main source for formaldehyde. Table 6.3 shows the current standards used in Europe, Australia and New Zealand, the United States of America and Japan (Salem and Böhm, 2013). In Europe, this regulation is called the E1 emission class and is based on a number of European testing standards, which require the formaldehyde emission of a product be less than 0.1 mg/m^3.

Labelling schemes are voluntary but have contributed to the development of low-emission products (Yrieix *et al.*, 2010). Some European member states have established mandatory requirements on VOC emissions from building products. Germany launched the Ausschuss zur gesundheitlichen Bewertung von Bauprodukten (*AgBB*) scheme in the aim to control potential indoor emissions sources such as flooring (Allen *et al.*, 2016; Makowski and Ohlmeyer, 2005; Roffael, 2006; Yrieix *et al.*, 2010). Its

Table 6.3 Current formaldehyde emissions standards for wood-based panels around the world (Salem and Böhm, 2013)

Country	Standard	Test method	Board class	Limit value
Europe	EN 13986 (CEN, 2005)	EN 717-1 (CEN, 2004)	E1-PB, MDF, OSB	≤0.1 ppm
		EN 120 (CEN, 1992)		≤8 mg/100 g of oven dry board
		EN 717-1 (CEN, 2004)	E1-PLW	≤0.1 ppm
		EN 717-2 (CEN, 1994)		≤3.5 mg/(h m^2)
		EN 717-1 (CEN, 2004)	E2-PB, MDF and OSB	>0.1 ppm
		EN 120 (CEN, 1992)		>8 ≤ 30 mg/g (oven dry)
		EN 717-1 (CEN, 2004)	E2-PLW	>0.1 ppm
		EN 717-2 (CEN, 1994)		>3.5 ≤ 8.0 mg/(h m-)0.1 ppm
Australia and New Zealand	AS/NZS 1859-1 (AS/NZA, 2004a) and 1859-2 (AS/NZS, 2004b)	AS/NZS 4266.16 (AS/NZS, 2004c) (desiccator)	E0-PB and MDF	≤0.5 mg/L
			E1-PB	≤1.5 mg/L
			E1-MDF	≤1.0 mg/L
			E2-PB and MDF	≤4.5 mg/L
US	ANSI A 208.1 (ANSI, 2016a) and 208.2 (ANSI, 2016b)	ASTM E1333-96 (ASTM (2002)) (large chamber)	PB	≤0.18 or 0.09 ppm
			MDF	≤0.21 or 0.11 ppm
Japan	JIS A 5908 (JIS, 2015) and 5905 (JIS, 2014)	JIS A 1460 (JIS (2001)) (desiccator)	F**	≤1.5 mg/L
			F***/'E0'	≤0.5 mg/L
			F****/'SE0'	≤0.3 mg/L

main task is to develop a uniform health-related assessment scheme for products that potentially emit VOC that maybe harmful to human health. Such labelling schemes aid developers and designers in selecting appropriate construction and insulation materials and encourage manufacturers to produce low-emitting products. Other labelling schemes include the indoor climate labelling scheme in Denmark and Norway based on odour or airway irritation thresholds; the B&Q paint policy scheme in the United Kingdom, which labels products with the percentage VOC emission; the Finnish labelling scheme with different categories (M1–M3) based on emissions of formaldehyde, ammonia, TVOC and carcinogenic compounds; and the German Association of Wallcovering Manufacturers that limits formaldehyde air emissions to $<60\,\mu/m^3$ from building products and limits heavy metals (Wolkoff, 2003).

6.4.9 Conclusion

An unforeseen consequence of increasing airtightness of buildings, in the pursuit of improved energy efficiency, is the building up of indoor air pollutants, VOCs and biological contaminants, to potentially harmful levels. The sources of VOCs are vast and can be divided into primary or secondary pollutants. The release of the VOCs from their source is influenced by human occupants, temperature, air velocity, RH and VOC characteristics. There is evidence that this build-up of such VOCs can adversely affect human health and contribute to sick building syndrome.

Efforts to reduce the build-up of indoor pollutants can be tackled on four levels: individual occupants, architects and developers, manufacturers and government. For true success, the latter three must work together to bring about better awareness of indoor pollution, fund scientific research into alternatives and multifunctional materials that will actively absorb and sequester VOCs and mycotoxins during their service life.

6.5 Bio-based materials and human well-being in the built environment

M.D. Burnard[*,†,‡]
[*]University of Primorska, Koper, Slovenia
[†]Abelium R&D, Ljubljana, Slovenia
[‡]InnoRenew CoE, Izola, Slovenia

6.5.1 Introduction

The built environment has a strong impact on both human and environmental health. Buildings and the infrastructure surrounding them consume great quantities of materials and energy during construction, operations, and eventual deconstruction at the end of the buildings life (Sinha *et al.*, 2013). There are accepted measures for analysing the environmental impacts of buildings and the materials and activities surrounding them such as life-cycle costing and assessment (ISO/IEC, 2006). As with environmental impacts, the built environment affects the people who use it in a variety of ways including psychologically, socially and physiologically. However, unlike the environmental

impacts of the built environment, the methods for understanding how buildings impact their users are not currently as well established.

Human health impacts in buildings stem from different elements and aspects of the building itself. These include the environment and location of the building, its design, materials, maintenance, accessibility, safety and the management of the building (in terms of thermal comfort, lighting, etc.). Certain health impacts are easier to understand, and control, than others. For example, emissions from materials (such as formaldehyde) in buildings are readily assessable and limits are placed on these emissions by legislation in many places (EPA, 2016; CEN, 1992). Emission measurements, though, are an indirect measure of the impact buildings have on human health impact and are focused on preventing harm.

Harm prevention is an incredibly important aspect of building design, maintenance and management, but modern building design paradigms are pushing beyond preventative measures and are beginning to incorporate both environmental and human health interventions that are intended to create positive effects (Derr and Kellert, 2013; Dolan *et al.*, 2016; Mang and Reed, 2012). For building users, these positive effects include health and behaviour impacts, which can translate to reduced pressures on health care systems, better job performance and more time at work (Danna and Griffin, 1999). This chapter will examine some of the primary concerns related to human health in the built environment, the interventions that can be used to create positive health impacts, as well as the design paradigms and research examining positive health interventions in the built environment. In each case, emphasis will be placed on the role of bio-based materials.

6.5.2 Primary concerns with human well-being in the builtenvironment

There are a variety of suggested frameworks for understanding and mitigating the negative effects buildings can have on occupants. For example, Kellert (2008) identifies six key principles for implementing biophilic design, which imparts improved human well-being in the built environment by supporting the innate connection between humans and life or life-like processes in nature. These principles include environmental features in the building, using natural shapes and forms, including natural patterns and processes, varying light and space, supporting place-base relationships and supporting the evolved human relationship with nature. Another recent framework is the sound, air, light, image, ergonomics and tint (*SALIENT*) checklist to understand how buildings affect what we do and how we feel (Dolan *et al.*, 2016). This list itemises seven factors that affect human well-being in the built environment: sound, air, lighting, image, ergonomics, nature and tint (colour) (Dolan *et al.*, 2016).

When negative human health and well-being effects associated with spending time in built environments manifest, they do so in several ways ranging from increased time away from work, greater stress, reduced work performance and direct health impacts. Briefly, these effects may be the following:

- Symptoms of illnesses – frequently observed as a variety of potentially connected symptoms often referred to as sick building syndrome (*SBS*) (Finnegan *et al.*, 1984).
- Psychophysiological stress – increased physical or social stress and a reduced ability to recover from stress (Fell, 2010).

- Directed attention deficits – reduced ability to recover from focusing one's attention (Hartig *et al.*, 1997).
- Ergonomic problems – musculoskeletal issues related to a lack of ergonomic interventions (Attaianese and Duca, 2012).

The links between elements of buildings and the effect imparted on building users are not always clear, and in many cases, a combination of elements are likely to jointly contribute. Furthermore, because place and local traditions play a role in how users perceive their environment, the effect of different design decisions may vary between places. Whilst culture may impact how users perceive their built environment, perceptions of building material naturalness are unlikely to vary significantly (Burnard *et al.*, 2015). The combination of material use and design choices that reflect natural environments are important aspects of imparting positive health impacts for building users.

Beyond perceptions, material selection also has direct effects on health impacts in the built environment, especially related to indoor air quality. Bio-based materials, and the adhesives, coatings, other treatments used on them, release VOCs into the environment (Gallego *et al.*, 2009; Jensen *et al.*, 2001; Manninen *et al.*, 2002). The amount and type of VOCs vary based on species, treatment and product (cf. Bulian and Fragassa, 2016). Regulations limiting the type or amount present in products used in buildings exist in many places and are often further limited when green building systems are followed (Bulian and Fragassa, 2016).

Understanding the performance of bio-based materials in terms of fitness for use (e.g. structural suitability), their environmental impact and their potential for contributing to positive health impacts in the built environment is critical for developing building paradigms that focus on positive impacts, instead of minimising negative impacts.

6.5.2.1 Psychophysiological well-being

Psychophysiological well-being can be considered as a state of a network of interdependent mental, emotional and physiological systems (McCraty *et al.*, 2009). Within this framework, the places people spend their time can affect their well-being by interacting with each system in the psychophysiological network. VOCs and other contaminants in the air directly impact physiological systems, which, in turn, affect mental and emotional state. Similarly, perceptions of the environment impact emotional and mental states and cause direct physiological impacts. Physical aspects of the built environment such as ergonomic function, safety, and accessibility also affect an individual in this framework.

The benefits that may be imparted by ones built environment include

- reduced psychophysiological stress, the ability to cope better with stressful events and situations, and increased recovery from stress;
- reduced time away from work due to illness;
- increased connection with and care for the natural environment;
- support for increased social cohesion; and
- support for more activity in typically sedentary lifestyles.

These benefits and others can be imparted by user perceptions of materials, building design and ergonomic interventions, views and inclusion of nature in the built environment, and material properties affecting indoor air quality, thermal comfort, etc.

Monitoring human well-being in the built environment requires understanding how humans interact with their surroundings, how perceived and physical stress are affected by buildings, how materials and building systems management impact indoor air quality, and many other aspects of the complex relationship between humans and the built environment. In many cases, common monitoring systems are indicative or indirect measurements of impacts on occupants and therefore difficult to directly relate to health impacts.

For example, measurements such as temperature, RH, lighting and airflow are straightforward to collect and interpret, but determining their impact on human health is more challenging. Upper and lower limits are generally suggested for thermal comfort indicators (e.g. temperature and RH) in standards such as ISO 7730 (ISO (2005)). These limits are expected to provide an acceptable level of comfort, but the specific contribution of materials to these values is not well known. Properties of bio-based materials such as thermal capacity or latent-heat-impact indoor environments, if better understood, may be able to be used to reduce mechanical interventions in the built environment (Kraniotis *et al.*, 2016).

Direct measurements of human well-being are more difficult to collect. Subjective measures of well-being may be derived by collecting user mood and comfort status, reports of illness, sick days taken, etc. but require human input and may vary greatly between users. Biological indicators of health and well-being (particularly stress and activity) are useful indicators of the actual state of building users but are more difficult and occasionally intrusive to collect. This difficulty and the nascent state of the field have led to relatively few studies into human health and well-being impacts of materials or buildings (for a review of human stress studies related to wood, see Burnard and Kutnar, 2015). Despite this shortcoming, many aspects considered to be strongly related to occupant well-being are studied for different building materials, often in an effort to explore the properties of new processes and products or to prove that they meet defined standards for use.

6.5.2.2 Factors impacting well-being in buildings

The primary factors that impact human well-being in the built environment are related to materials, building and product performance, ergonomics, user perceptions of their environment and the activities users perform in buildings.

Many aspects of each factor contribute to the impact felt by building users. For example, the material (e.g. an exposed wood beam) can be perceived by the user to impart safety (as a structural element), warmth (in colour and thermal comfort), restoration (associated with nature); will have specific properties related to acoustics, thermal comfort, lighting, VOC emissions, etc.; and may be functionalised beyond its basic intent (e.g. supporting other elements of the building). These factors can be influenced by processing, maintenance, natural processes (such as decay and changes in colour), etc.

Material and product related

Here, material- and product-related factors that impact occupant health are considered those directly related to the material, product components and processes. Wood and

other bio-based materials are known to contain and emit VOCs and other contaminants as they go through drying processes (natural or otherwise). In recent years, formaldehyde has been a primary concern and has been limited by statue in many areas (e.g. by the Environmental Protection Agency (EPA) in the United States (EPA, 2016), by the CEN 120 (CEN (1992)) and other agencies worldwide).

VOC emissions from wood and other bio-based materials are biogenic and are part of natural processes. The amount and type of emissions are dependent on species and affected by processes such as drying or thermal treatment. For example, differences in the types and quantities of emissions varied between air-dried and heat-treated Scots pine, as reported by (Manninen *et al.*, 2002). It is possible for reactions to occur as wood dries causing emissions of compounds not originally present in the material as well (Milota, 2000). Subjecting wood to thermal processes (e.g. drying, heat-treating and thermal-mechanical treatments) before use can limit the amount of emissions after installation (Milota *et al.*, 2007).

Emissions released by composite products, especially those of glued composites using adhesives with formaldehyde, are also a major concern as they are present to a great degree in the furniture used in buildings and other building components (Huang and Li, 2007; Jang *et al.*, 2011). Whilst alternatives (e.g. soy-based adhesives) are under development, their performance often suffers in terms of strength or susceptibility to water (Huang and Li, 2007; Schwarzkopf *et al.*, 2010). Other processes impose similar concerns: wood preservatives, fire retardants and coatings often contain contaminants, which may be emitted into buildings or outdoor spaces (Yu and Kim, 2012). The inclusion of these contaminants in building products impedes their use in recycling schemes, as well (Yu and Kim, 2012).

Processes that affect appearance (such as some coatings or mechanical processing that can obscure recognisability as a natural product) are likely to reduce the ability of occupants to gain restorative effects from the materials (Burnard *et al.*, 2015). Similarly, these processes are likely to impact user preference for materials as well, which can have similar psychological effects on building occupants. Coatings and other treatments also impact the degree of perceived warmth (a haptic response felt by users when touching a material) (Bhatta and Kyttä, 2016). In principle, when a material feels warmer at a lower temperature than another, energy used to heat the material (e.g. flooring) can be saved whilst maintaining acceptable levels of thermal comfort (Bhatta and Kyttä, 2016).

Performance

The performance of materials in buildings relies on a complex system that includes building systems management that control electronic and mechanical components, materials, use patterns, outdoor weather, building design and more. Bio-based materials can play many roles in building performance. Some recent research trends have been to functionalise wood and wood products, along with other bio-based materials, to provide improved material properties such as fire retardancy, hydrophobicity and resistance to weathering (Petrič, 2013).

In the presence of moisture, bio-based materials can be a nutrient source for fungi in build environment (WHO-E, 2009). Fungi can have a variety of negative effects

ranging from damage to the buildings structure (in the case of wood-rotting fungi) and can become airborne potentially harming building users (WHO-E, 2009). Fungi, moulds and associated bacteria are known to emit VOCs (often termed microbial volatile organic compounds – *MVOCs*), allergens and a variety of toxins (WHO-E, 2009; Sahlberg *et al.*, 2013). However, evidence that inhalation of these substances cause human health problems remains unconvincing (as opposed to evidence that ingestion of fungi causes health problems), according to Terr (2009). Whilst studies continue to examine airborne toxins related to moisture and fungi in the built environment, experimentally controlled studies are impossible due to health concerns (Terr, 2009). Nonetheless, limiting the fungal growth (and other phenomena related to moisture and dampness) in buildings should be a key aspect of material selection, building design and construction methods.

The varying colour, treatments and use of bio-based indoor products impact lighting needs and the visual comfort of spaces in buildings (Jafarian *et al.*, 2016). There is an opportunity to optimise artificial and day lighting and occupant visual comfort by using wood indoors of various colours, patterns (imparted by grain or designed) and amounts to alter brightness, colour, temperature, perceived glare and other attributes through intelligent use bio-based products (Jafarian et al., 2016).

Acoustics in buildings are also affected by material selection for structural and decorative materials. Bio-based materials, including flax, cellulose, wood wool, and cork, have been shown to be effective in providing good acoustic performance (Asdrubali, 2006).

Human factors/ergonomics

Human factors/ergonomics (*HFE*) is a scientific discipline that is itself primarily concerned with human well-being and performance; it seeks to optimise systems to maximise its concerns (Dul *et al.*, 2012). HFE enhances well-being by implementing design changes and interventions in buildings, products, and systems to reduce negative impacts on users. The types of interventions may relate to

- safety (e.g. railings in bathrooms and along walkways),
- accessibility (e.g. ramps, room size, optimising worker movement in an office or factory) or
- activity (e.g. reducing time in sedentary positions whilst at work and providing activities to mitigate the effect).

There are many opportunities for bio-based materials to play a role in these interventions, and the overall well-being goals are well aligned with optimised wood use in buildings.

Using wood as a safety intervention for the elderly can help users navigate and safely use bathrooms (Verma, 2016). The colour contrast of wood and typically white-porcelain components of bathroom environments helps users (especially those with diseases like Alzheimer's) to more easily recognise and use components of bathrooms (Verma, 2016). Similarly, bio-based may be used for a variety of interventions including ergonomically designed furniture, built-up handles on utensils, railings, ramps, etc.

Design related

The variety of HFE, material and product and performance factors discussed above require an overarching framework to produce positive human health impacts. Several design paradigms exist for including elements of nature in the built environment, including biophilic design (Kellert, 2008), restorative environmental design (*RED*) (Derr and Kellert, 2013), regenerative design (Mang and Reed, 2012), restorative environmental and ergonomic design (*REED*) (Burnard *et al.*, 2016). These design paradigms each place emphasis on including nature in the built environment; however, except for REED, the focus is less on material choices and more on access to nature through views of windows, water features, plants, etc. The specifics of material selection are often overlooked and relegated to concerns of cost and environmental impact. Whilst these concerns are valid, creating positive impacts requires making evidence-based decisions for a variety of design choices.

These design paradigms show continual growth in the treatment of nature and naturalness in building design. However, in all cases, access to more evidence of the various effects is needed to inform design decision. Furthermore, documentation on how to properly use materials in to achieve positive effects is needed. In addition to conducting and reporting research, scientists, designers, material and product manufacturers, users and other stakeholders must come together and develop design strategies and documentation that create positive human health impacts.

6.5.2.3 Measuring impact

Measuring the impact of design decisions, material selection, and building use on human health is often a considerable challenge. In cases where standards exist to determine indirect health indicators (e.g. to determine VOC emissions, thermal properties and acoustic properties), these can be used as an initial step in determining the impact products or materials will have on users in the built environment. However, these indicators do not directly reveal the health impacts of materials and their use; they reveal an aspect to be considered in design and material selection.

The effects building material selection has on human health can be determined in a variety of ways, including monitoring human stress and stress recovery. Stress can be monitored unobtrusively in experimental and real-life settings using indicators such as heart rate, heart-rate variability, galvanic skin response and salivary free cortisol levels – ideally using multiple indicators (Burnard and Kutnar, 2015). These methods have been used to determine the stress recovery effects of outdoor natural environments (e.g. Tyrväinen *et al.*, 2014). Stress is a direct indicator of an important health impact that designers can readily consider once more evidence is gathered and reported.

Self-reported psychological assessment can also be a useful method for understanding occupant health in the built environment. Many scales and methods exist for determining user perceptions, mood and well-being. For example, the perceived restorativeness scale was originally developed by Hartig *et al.* (1997) and further developed by many other researchers including Pasini *et al.* (2014) who developed a shortened version (11 vs. 26 items). This scale has been used in many studies to describe how users perceive various indoor and outdoor environments

(e.g. Hug *et al.*, 2009; Hipp and Ogunseitan, 2011). Another common scale developed by Engvall *et al.* (2004) can be used to identify the degree to which a building may contribute to sick building syndrome.

Ideally, studies should be conducted in real-use situations (i.e. in either mock environments or actual environments that are experimentally controlled) that allow control for the many factors that may affect health outcomes. Whilst these studies can be expensive and lengthy, a body of evidence must be developed to appropriately determine the potential health impacts bio-based materials may have in the built environment.

6.5.3 Future prospects for bio-based materials and human health

Bio-based materials have the potential to contribute to positive human health impacts in the built environment. Bio-based materials can be functionalised in specific ways to improve indoor environmental quality by a variety of processes. They can provide a strong connection to nature, which is associated with restorative processes that allow building occupants to recover from physical and psychological stress or to recover resources expended by focusing one's attention and, consequently, to increase productivity and performance at the work place. Although there is a growing body of research into the human health impacts of bio-based material use, it is a nascent field that requires a strong interdisciplinary approach to research that includes designers, health professionals, ergonomists, material scientists and user and manufacturer input.

In framing research questions and material and product design, it is helpful to keep in mind a framework that supplies goals for material use. REED is a design paradigm that can inspire designers to creatively utilise materials and seek products that solve design problems. It can help manufacturers develop new products and target material property changes. It can guide researchers towards identifying new methods and processes for altering material properties and help them to find interdisciplinary projects that expand the scope of expertise contributing to creating positive health impacts in the buildings we all spend so much of our time in.

As the science progresses, building certification schemes should include positive human (and environmental) impacts into their rating systems. It is past time that all stakeholders in the built environment turn their attention towards positive impacts for occupants, the environment and society.

References

Abbott, S.P., 2002. Mycotoxins and indoor molds. Indoor Environ. Connect. 3, 14–24.

Al-Homoud, M., 2005. Performance characteristics and practical applications of common building thermal insulation materials. Build. Environ. 40 (3), 353–366.

Allen, N.D.C., Brewer, P.J., Brown, R.J.C., Lipscombe, R.P., Woods, P.T., 2016. International comparison of key volatile organic components in indoor air. Measurement 82, 476–481. http://dx.doi.org/10.1016/j.measurement.2016.01.027.

Almusaed, A., Almssad, A., 2015. Building materials in eco-energy houses from Iraq and Iran. Case Stud. Constr. Mater. 2, 42–54.

ANSI, 2016a. ANSI A208.1:2016. Particleboard. American National Standards Institute, Washington, DC, United States.

ANSI, 2016b. ANSI A208.2:2016. Medium Density Fiberboard (MDF) for Interior Applications. American National Standards Institute, Washington, DC, United States.

ASTM, 2002. ASTM E 1333-96:2002. Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber Method. American Society for Testing and Materials (ASTM), West Conshohocken, PA, United States.

Andersen, I., Lundqvist, G.R., Mølhave, L., 1975. Indoor air pollution due to chipboard used as a construction material. Atmos. Environ. 9, 1121–1127. http://dx.doi.org/10.1016/0004-6981(75)90188-2.

AS/NZS, 2004a. AS/NZS 1859-1:2004. Reconstituted Wood-Based Panels – Specifications Particleboard. Standards Australia, Sydney, NSW, Australia.

AS/NZS, 2004b. AS/NZS 1859-2:2004. Reconstituted Wood-Based Panels – Specifications Dry-Processed Fibreboard. Standards Australia, Sydney, NSW, Australia.

AS/NZS, 2004c. AS/NZS 4266.16:2004. Reconstituted Wood-Based Panels – Methods of Test Formaldehyde Emission – Desiccator Method. Standards Australia, Sydney, NSW, Australia.

Ascione, F., Bianco, N., De Stasio, C., Mauro, G.M., Vanoli, G.P., 2015. A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. Energy Build. 88, 78–90.

Asdrubali, F., 2006. Survey on the acoustical properties of new sustainable materials for noise control. In: Proceedings of Euronoise 2006, Tampere, Finland, pp. 1–10.

Asdrubali, F., Bianchi, F., Cotana, F., D'Alessandro, F., Pertosa, M., Pisello, A.L., Schiavoni, S., 2016a. Experimental thermo-acoustic characterization of innovative common reed bio-based panels for building envelope. Build. Environ. 102, 217–229.

Asdrubali, F., D'Alessandro, F., Schiavoni, S., 2015. A review of unconventional sustainable building insulation materials. Sustain. Mater. Technol. 4, 1–15.

Asdrubali, F., Pisello, A.L., D'Alessandro, F., Bianchi, F., Fabiani, C., Cornicchia, M., Rotili, A., 2016b. Experimental and numerical characterization of innovative cardboard based panels: thermal and acoustic performance analysis and life cycle assessment. Build. Environ. 95, 145–159.

Attaianese, E., Duca, G., 2012. Human factors and ergonomic principles in building design for life and work activities: an applied methodology. Theor. Issues Ergon. Sci. 13 (2), 187–202. http://dx.doi.org/10.1080/1463922X.2010.504286.

Ayrilmis, N., Buyuksari, U., Avci, E., Koc, E., 2009. Utilization of pine (*Pinus pinea* L.) cone in manufacture of wood based composite. For. Ecol. Manag. 259, 65–70. http://dx.doi.org/10.1016/j.foreco.2009.09.043.

Barreneche, C., Navarro, L., de Gracia, A., Fernandez, A., Cabeza, L.F., 2016. In situ thermal and acoustic performance and environmental impact of the introduction of a shape-stabilized PCM layer for building applications. Renew. Energy 85, 281–286.

Ber, B., Premrov, M., Štrukelj, A., Kuhta, M., 2014. Experimental investigations of timber–glass composite wall panels. Constr. Build. Mater. 66, 235–246.

Berardi, U., Iannace, G., 2015. Acoustic characterization of natural fibers for sound absorption applications. Build. Environ. 94, 840–852.

Bhatta, S., Kyttä, M., 2016. Sensory experiences of wood: achieving the energy efficiency and user satisfaction. In: Cronhjort, Y., Hughes, M., Sahi, K., Tukiainen, P. (Eds.), Functional Wood. Aalto University, Helsinki, pp. 96–99.

Boran, S., Usta, M., Ondaral, S., Gümüşkaya, E., 2012. The efficiency of tannin as a formaldehyde scavenger chemical in medium density fiberboard. Compos. Part B 43, 2487–2491. http://dx.doi.org/10.1016/j.compositesb.2011.08.004.

Brás, A., 2016. Embodied carbon minimisation of retrofit solutions for walls. Proc. ICE Eng. Sustain. http://dx.doi.org/10.1680/jensu.15.00047.

Brás, A., Gomes, V., 2015. LCA implementation in the selection of thermal enhanced mortars for energetic rehabilitation of school buildings. Energy Build. 92, 1–9.

Brás, A., Gonçalves, F., Faustino, P., 2014a. Cork-based mortars for thermal bridges correction in a dwelling. Thermal performance and cost evaluation. Energy Build. 72, 296–308.

Brás, A., Gonçalves, F., Faustino, P., 2014b. Economic evaluation of the energy consumption and thermal passive performance of Portuguese dwellings. Energy Build. 76, 304–315.

Brás, A., Leal, M., Faria, P., 2013. Cement-cork mortars for thermal bridges correction. Comparison with cement-EPS mortars performance. Constr. Build. Mater. 49, 315–327.

Brás, A., Valença, A., Faria, P., 2016. Performance-based methods for masonry building rehabilitation using innovative leaching and hygrothermal risk analyses. Sustain. Cities Soc. http://dx.doi.org/10.1016/j.scs.2016.09.010.

Brown, S.K., Sim, M.R., Abramson, M.J., Gray, C.N., 1994. Concentrations of volatile organic compounds in indoor air – a review. Indoor Air 4, 123–134. http://dx.doi.org/10.1111/j.1600-0668.1994.t01-2-00007.x.

Bulian, F., Fragassa, C., 2016. VOC emissions from wood products and furniture: a survey about legislation, standards and measures referred to different materials. FME Trans. 44 (4), 359.

Burnard, M.D., Nyrud, A.Q., Bysheim, K., et al., 2015. Building material naturalness: perceptions from Finland, Norway and Slovenia. Indoor Built Environ, 1–16. http://dx.doi.org/10.1177/1420326X15605162.

Burnard, M.D., Kutnar, A., 2015. Wood and human stress in the built indoor environment: a review. Wood Sci. Technol. 49, 969–986. http://dx.doi.org/10.1007/s00226-015-0747-3.

Burnard, M.D., Schwarzkopf, M.J., Kuntar, A., 2016. Interdisciplinary approaches to developing wood modification processes for sustainable building and beyond – INNORENEW COE. In: Proceedings of the World Conference on Timber Engineering, August 22–25, 2016, Vienna, Austria. Technical University of Vienna, Vienna, Austria.

Buyuksari, U., Ayrilmis, N., Avci, E., Koc, E., 2010. Evaluation of the physical, mechanical properties and formaldehyde emission of particleboard manufactured from waste stone pine (*Pinus pinea* L.) cones. Bioresour. Technol. 101, 255–259. http://dx.doi.org/10.1016/j.biortech.2009.08.038.

Cao, J.-S., Lin, J.-X., Fang, F., Zhang, M.-T., Hu, Z.-R., 2014. A new absorbent by modifying walnut shell for the removal of anionic dye: kinetic and thermodynamic studies. Bioresour. Technol. 163, 199–205. http://dx.doi.org/10.1016/j.biortech.2014.04.046.

Cardoso, S., Nunes, L., Faria, P., 2015a. Characterization tests for insulation boards made from corncob and natural glues. In: Jones, D., Brischke, C., Kers, J., Poltimae, T., Schmid, J. (Eds.), Technical Workshop "Performance Testing and Testing Methodologies of Non-Wood Biobased Materials", Joint COST ACTION FP1303 & FP1404, Tallinn University of Technology, Estonia 4–5 March 2015, Book of Abstracts. SP Technical Research Institute of Sweden, pp. 52–53.

Cardoso, S., Nunes, L., Faria, P., 2015b. Bio-based adhesives for wood-based panels – a review. Ciência Tecnol. Mater. 27 (2), 142–151 (in Portuguese).

Carneiro, P., Jerónimo, A., Silva, V., Cartaxo, F., Faria, P., 2016. Improving building technologies with a sustainable strategy. Procedia Soc. Behav. Sci. 216, 829–840.

Cellat, K., Beyhan, B., Güngör, C., Konuklu, Y., Karahan, O., Dündar, C., Paksoy, H., 2015. Thermal enhancement of concrete by adding bio-based fatty acids as phase change materials. Energy Build. 106, 156–163.

CEN, 1992. EN 120:1992. Wood Based Panels – Determination of Formaldehyde Content – Extraction Method Called the Perforator Method. European Committee for Standardization, Brussels, Belgium. This has been superseded by BS EN ISO 12460-5:2015. Wood-Based panels – Determination of Formaldehyde Release – Extraction Method (Called the Perforator Method. European Committee for Standardization, Brussels, Belgium.

CEN, 1994. EN 717-2:1994. Wood-Based Panels – Determination of Formaldehyde Release – Part 2: Formaldehyde Release by the Gas Analysis Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2004. EN 717-1:2004. Wood-Based Panels – Determination of Formaldehyde Release – Part 1: Formaldehyde Emission by the Chamber Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2005. EN 13986:2005. Wood-Based Panels for Use in Construction – Characteristics, Evaluation of Conformity and Marking. European Committee for Standardization, Brussels, Belgium.

CEN, 2007/2009. EN 13501-1/A1:2007/2009. Fire Classification of Construction Products and Building Elements – Part 1: Classification Using Data from Reaction to Fire Tests. European Committee for Standardization, Brussels, Belgium.

Chau, C., Leung, T., Ng, W., 2015. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Appl. Energy 143, 395–413.

Chybík, J., 2009. Natural Building Materials. Grada Publishing, Prague, ISBN: 978-80-247-2532-1.

Conner, A.H., 1996. Urea-Formaldehyde Adhesive Resins. USDA Forest Service, Forest Products Laboratory, Madison, WI.

Cui, Y., Xie, J., Liu, J., Pan, S., 2015. Review of phase change materials integrated in building walls for energy saving. Procedia Eng. 121, 763–770.

Curling, S.F., Loxton, C., Ormondroyd, G.A., 2012. A rapid method for investigating the absorption of formaldehyde from air by wool. J. Mater. Sci. 47, 3248–3251. http://dx.doi.org/10.1007/s10853-011-6163-7.

Danna, K., Griffin, R.W., 1999. Health and well-being in the workplace: a review and synthesis of the literature. J. Manag. 25 (3), 357–384. http://dx.doi.org/10.1177/014920639902500305.

De Long, J., 1923. Insulating Material and Process of Manufacturing Same. US Patent 1442328 A.

Derr, V., Kellert, S.R., 2013. Making children's environments 'R.E.D.': restorative environmental design and its relationship to sustainable design. In: Pavlides, E., Wells, J. (Eds.), Proceedings of the 44th Annual Conference of the Environmental Design Research Association.

Dolan, P., Foy, C., Smith, S., 2016. The SALIENT Checklist: gathering up the ways in which built environments affect what we do and how we feel. Buildings 6 (1), 9. http://dx.doi.org/10.1177/014920639902500305.

Dowling, A., Mathias, J.A., 2007. Experimental determination of the insulating ability of corn by-products. J. Sustain. Agric. 30, 15–27.

Dul, J., Bruder, R., Buckle, P., Carayon, P., Falzon, P., Marras, W.S., Wilson, J.R., van der Doelen, B., 2012. A strategy for human factors/ergonomics: developing the discipline and profession. Ergonomics 55 (4), 377–395. http://dx.doi.org/10.1080/00140139.2012.661087.

EC, 2016. EU Climate Action – European Commission [WWW Document]. URL http://ec.europa.eu/clima/citizens/eu/index_en.htm (accessed 11.1.16).

Ekici, B., Gulten, A., Aksoy, U., 2012. A study on the optimum insulation thicknesses of various types of external walls with respect to different materials, fuels and climate zones in Turkey. Appl. Energy 92, 211–217.

Engvall, K., Norrby, C., Sandstedt, E., 2004. The Stockholm Indoor Environment Questionnaire: a sociologically based tool for the assessment of indoor environment and health in dwellings. Indoor Air 14 (1), 24–33. http://dx.doi.org/10.1111/j.1600-0668.2004.00204.x.

Environmental Protection Agency (EPA), 2016. Formaldehyde Emission Standards for Composite Wood Products. Docket Numbers: EPA-HQ-OPPT-2012-0018, EPA-HQ-OPPT-2011-0380.

European Commission, 2011. A Road Map for Moving to a Competitive Low Carbon Economy in 2050. European Commission, Brussels.

European Commission, 2012a. Innovating for Sustainable Growth: A Bioeconomy for Europe. European Commission, Brussels.

European Commission, 2012b. Directive 2012/27/EU of the European Parliament and of the Council of 25 October. European Commission, Brussels.

Fang, L., Clausen, G., Fanger, P.O., 1999. Impact of temperature and humidity on chemical and sensory emissions from building materials. Indoor Air 9, 193–201. http://dx.doi.org/10.1111/j.1600-0668.1999.t01-1-00006.x.

Faria, P., Carneiro, P., Jerónimo, A., Malheiro, D., 2016. ReedCob – an eco-efficient building technology for monolithic walls based on earth and reeds. In: Troya, T., Galván, J., Jones, D. (Eds.), 4th Conference COST ACTION FP1303 – Designing with Bio-Based Materials – Challenges and Opportunities. INIA – CSIC, Madrid, 24–25 February 2016, Book of Abstracts. INIA and IETcc – CSIS, Madrid, pp. 79–80.

Fell, D.R., 2010. Wood in the Human Environment: Restorative Properties of Wood in the Built Indoor Environment. University of British Columbia, Vancouver, CA.

Finnegan, M.J., Pickering, C.A., Burge, P.S., 1984. The sick building syndrome: prevalence studies. Br. Med. J. (Clin. Res. Ed.) 289 (6458), 1573–1575. http://dx.doi.org/10.1136/bmj.289.6458.1573.

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., Buhe, C., Woloszyn, M., 2015. Methodological challenges and developments in LCA of low energy buildings: application to biogenic carbon and global warming assessment. Build. Environ. 90, 51–59.

Freitas, V., et al., 2012. Heat, air and moisture transfer terminology – parameters and concepts. CIB – W040 Heat and Moisture Transfer in Buildings. FEUP Edições, Porto.

Gallego, E., Roca, X., Perales, J.F., et al., 2009. Determining indoor air quality and identifying the origin of odour episodes in indoor environments. J. Environ. Sci. 21 (3), 333–339. http://dx.doi.org/10.1016/S1001-0742(08)62273-1.

Ghoshal, A.K., Manjare, S.D., 2002. Selection of appropriate adsorption technique for recovery of VOCs: an analysis. J. Loss Prev. Process Ind. 15, 413–421. http://dx.doi.org/10.1016/S0950-4230(02)00042-6.

Haghighat, F., De Bellis, L., 1998. Material emission rates: literature review, and the impact of indoor air temperature and relative humidity. Build. Environ. 33, 261–277. http://dx.doi.org/10.1016/S0360-1323(97)00060-7.

Hall, M., Lindsay, R., Krayenhoff, M. (Eds.), 2012. Modern Earth Buildings – Materials, Engineering, Constructions and Applications. Woodhead Publishing Series in Energy, ISBN: 978-0-85709-026-3.

Halvarsson, S., Edlund, H., Norgren, M., 2010. Wheat straw as raw material for manufacture of medium density fiberboard (MDF). BioResources 5, 1215–1231.

Harada, T., Hata, T., Ishihara, S., 1998. Thermal constants of wood during the heating process measured with the laser flash method. J. Wood Sci. 44, 425–431.

Hartig, T., Korpela, K., Evans, G.W., Gärling, T., 1997. A measure of restorative quality in environments. Scand. Hous. Plann. Res. 14, 175–194. http://dx.doi.org/10.1080/02815739708730435.

Hens, H., 2007. Building Physics – Heat, Air and Moisture. Ernst & Sohn, Berlin.
Hipp, J.A., Ogunseitan, O.A., 2011. Effect of environmental conditions on perceived psychological restorativeness of coastal parks. J. Environ. Psychol. 31 (4), 421–429. http://dx.doi.org/10.1016/j.jenvp.2011.08.008.
Hodgson, A.T., Beal, D., McIlvaine, J.E.R., 2002. Sources of formaldehyde, other aldehydes and terpenes in a new manufactured house. Indoor Air 12, 235–242. http://dx.doi.org/10.1034/j.1600-0668.2002.01129.x.
Holcroft, N., Shea, A., 2013. Moisture buffering and latent heat effects in natural fibre insulation materials. In: SB 14 – Sustainable Buildings, PT.
Huang, J., Li, K., 2007. A new soy flour-based adhesive for making interior type II plywood. J. Am. Oil Chem. Soc. 85 (1), 63–70. http://dx.doi.org/10.1007/s11746-007-1162-1.
Hug, S.M., Hartig, T., Hansmann, R., Seeland, K., Hornung, R., 2009. Restorative qualities of indoor and outdoor exercise settings as predictors of exercise frequency. Health Place 15 (4), 971–980. http://dx.doi.org/10.1016/j.healthplace.2009.03.002.
Hun, D.E., Corsi, R.L., Morandi, M.T., Siegel, J.A., 2010. Formaldehyde in residences: long-term indoor concentrations and influencing factors. Indoor Air 20, 196–203. http://dx.doi.org/10.1111/j.0905-6947.2010.00644.x.
ISO, 1998. ISO 10534-2:1998. Acoustics—Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes. Part 2: Transfer Function-Method. International Organization for Standardization, Geneva, Switzerland.
ISO, 2005. ISO 7730:2005. Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Organization for Standardization, Geneva, Switzerland. Available from: http://www.iso.org/iso/catalogue_detail.htm?csnumber=39155.
ISO/IEC, 2006. ISO/IEC 14040:2006. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva, Switzerland. Available from: http://www.iso.org/iso/catalogue_detail?csnumber=37456.
Jafarian, H., Demers, C.M.H., Blanchet, P., Landry, V., 2016. Impact of indoor use of wood on the quality of interior ambiances under overcast and clear skies: case study. BioResources 11, 1647–1663. http://dx.doi.org/10.15376/biores.11.1.1647-1663.
Jang, Y., Huang, J., Li, K., 2011. A new formaldehyde-free wood adhesive from renewable materials. Int. J. Adhes. Adhes. 31, 754–759. http://dx.doi.org/10.1016/j.ijadhadh.2011.07.003.
JIS, 2001. JIS A: 1460:2001. Building Boards. Determination of Formaldehyde Emission Desiccator Method. Japanese Standards Association, Tokyo, Japan.
JIS, 2014. JIS A: 5905:2015. Fiberboards. Japanese Standards Association, Tokyo, Japan.
JIS, 2015. JIS A: 5908:2015. Particleboards. Japanese Standards Association, Tokyo, Japan.
Jarvis, B.B., Miller, J.D., 2004. Mycotoxins as harmful indoor air contaminants. Appl. Microbiol. Biotechnol. 66, 367–372. http://dx.doi.org/10.1007/s00253-004-1753-9.
Jensen, L.K., Larsen, A., Mølhave, L., et al., 2001. Health evaluation of volatile organic compound (VOC) emissions from wood and wood-based materials. Arch. Environ. Health 56 (5), 419–432. http://dx.doi.org/10.1080/00039890109604477.
Kamke, F., Zylkowski, S., 1989. Effects of wood-based panel characteristics on thermal conductivity. For. Prod. J. 39, 19–24.
Kang, Y., Jeong, S., Wi, S., Kim, S., 2015. Energy efficient bio-based PCM with silica fume composites to apply in concrete for energy saving in buildings. Sol. Energy Mater. Sol. Cells 143, 430–434.
Kellert, S.R., 2008. Dimensions, elements and attributes of biophilic design. In: Kellert, S.R., Heerwagen, J., Mador, M. (Eds.), Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life, first ed. Wiley, Hoboken, pp. 3–19.

Kim, J.-W., Sohn, M.-H., Kim, D.-S., Sohn, S.-M., Kwon, Y.-S., 2001. Production of granular activated carbon from waste walnut shell and its adsorption characteristics for Cu^{2+} ion. J. Hazard. Mater. 85, 301–315. http://dx.doi.org/10.1016/S0304-3894(01)00239-4.

Kim, S., 2010. Control of formaldehyde and TVOC emission from wood-based flooring composites at various manufacturing processes by surface finishing. J. Hazard. Mater. 176, 14–19. http://dx.doi.org/10.1016/j.jhazmat.2009.03.113.

Kim, S., 2009. The reduction of indoor air pollutant from wood-based composite by adding pozzolan for building materials. Constr. Build. Mater. 23, 2319–2323. http://dx.doi.org/10.1016/j.conbuildmat.2008.11.008.

Kim, S., Kim, J.-A., Kim, H.-J., 2007. Application of field and laboratory emission cell (FLEC) to determine formaldehyde and VOCs emissions from wood-based composites. Mokchae Konghak 35, 24–27.

Kim, S., Kim, J.-A., Kim, H.-J., Do Kim, S., 2006. Determination of formaldehyde and TVOC emission factor from wood-based composites by small chamber method. Polym. Test. 25, 605–614. http://dx.doi.org/10.1016/j.polymertesting.2006.04.008.

Knudsen, K., Afshari, A., Ekberg, L., Lundgren, B., 2002. Impact of Ventilation Rate, Ozone and Limonene on Perceived Air Quality in Offices [WWW Document]. URL https://www.irbnet.de/daten/iconda/CIB6596.pdf (accessed 8.18.16).

Kobbing, J.F., Thevs, N., Zerbe, S., 2013. The utilisation of reed (*Phragmites australis*): a review. Mires Peat 13 (1), 1–14.

Korjenic, A., Zach, J., Hroudová, J., 2016. The use of insulating materials based on natural fibers in combination with plant facades in building constructions. Energy Build. 116, 45–58.

Kraniotis, D., Langouet, N., Orskaug, T., Nore, K., Glasø, G., 2016. Moisture buffering and latent heat sorption phenomena of a wood-based insulating sandwich panel. In: Proceedings of the World Conference on Timber Engineering, August 22–25, 2016, Vienna, Austria. Technical University of Vienna, Vienna, Austria.

Krus, M., Theuerkorn, W., Großkinsky, T., Kunzel, H., 2014. New sustainable and insulating building material made of cattail (typha). In: Proceedings of the 10th Nordic Symposium on Building Physics, Lund, 15–19 June. Fraunhofer-Publica.

Laborel-Préneron, A., Aubert, J.-E., Magniont, C., Tribout, C., Bertron, A., 2016. Plant aggregates and fibers in earth construction materials: a review. Constr. Build. Mater. 111, 719–734.

Latif, E., Lawrence, M., Shea, A., Waljer, P., 2015. Moisture buffer potential of experimental wall assemblies incorporating formulated hemp-lime. Build. Environ. 93 (2), 199–209.

Lee, J.-H., Kim, S., 2012. The determination of the adsorption performance of graphite for VOCs and formaldehyde. Energy Build. 46, 56–61. http://dx.doi.org/10.1016/j.enbuild.2011.10.046.

Lei, H., Du, G., Pizzi, A., Celzard, A., 2008. Influence of nanoclay on urea-formaldehyde resins for wood adhesives and its model. J. Appl. Polym. Sci. 109, 2442–2451. http://dx.doi.org/10.1002/app.28359.

Lima, J., Faria, P., 2016. Eco-efficient earthen plasters: the influence of the addition of natural fibers. In: Fangueiro, R., Rana, S. (Eds.), Natural Fibres: Advances in Science and Technology Towards Industrial Applications 12. RILEM Bookseries, Springer, Dordrecht, pp. 315–327.

Limam, A., Zerizer, A., Quenard, D., Sallee, H., Chenak, A., 2016. Experimental thermal characterization of bio-based materials (Aleppo Pine wood, cork and their composites) for building insulation. Energy Build. 116, 89–95.

Lin, Q., Yang, G., Liu, J., Rao, J., 2006. Property of nano-SiO_2/urea formaldehyde resin. Front. For. China 1, 230. http://dx.doi.org/10.1007/s11461-006-0024-6.

Maderuelo-Sanz, R., Barrigón Morillas, J.M., Gómez Escobar, V., 2014. Acoustical performance of loose cork granulates. Eur. J. Wood Prod. 72, 321. http://dx.doi.org/10.1007/s00107-014-0784-x.

Madurwar, M.V., Ralegaonkar, R.V., Mandavgane, S.A., 2013. Application of agro-waste for sustainable construction materials: a review. Constr. Build. Mater. 38, 872–878.

Magniont, C., Escadeillas, G., Coutand, M., 2012. Use of plant aggregates in building ecomaterials. Eur. J. Environ. Civil Eng. 16 (1), s17–s33.

Makowski, M., Ohlmeyer, M., 2005. Influences on VOC Emissions of Wood-Based Panels. In: 9th European Panel Products Symposium. Presented at the 9th European Panel Products Symposium, Llandudno, Wales, pp. 106–114.

Mang, P., Reed, B., 2012. Designing from place: a regenerative framework and methodology. Build. Res. Inf. 40 (1), 23–38. http://dx.doi.org/10.1080/09613218.2012.621341.

Manninen, A.-M., Pasanen, P., Holopainen, J.K., 2002. Comparing the VOC emissions between air-dried and heat-treated Scots pine wood. Atmos. Environ. 36 (11), 1763–1768. http://dx.doi.org/10.1016/S1352-2310(02)00152-8.

Mansour, E., Curling, S., Stéphan, A., Ormondroyd, G., 2016. Absorption of volatile organic compounds by different wool types. Green Mater. 4, 1–7. http://dx.doi.org/10.1680/jgrma.15.00031.

Markowicz, P., Larsson, L., 2014. Influence of relative humidity on VOC concentrations in indoor air. Environ. Sci. Pollut. Res. 22, 5772–5779. http://dx.doi.org/10.1007/s11356-014-3678-x.

McCraty, R., Atkinson, M., Tomasino, D., et al., 2009. The coherent heart: heart-brain interactions, psychophysiological coherence, and the emergence of system-wide order. Integral Rev. 5 (2), 10–115.

Meyer, B., Boehme, C., 1997. Formaldehyde emission from solid wood. For. Prod. J. 47, 45–48.

Miljan, M., Miljan, M.-J., Miljan, J., Akermann, K., Karja, K., 2014. Thermal transmittance of reed-insulated walls in a purpose-built test house. Mires Peat 13 (7), 1–12.

Milota, M.R., 2000. Emissions from wood drying: the science and the issues. For. Prod. J. 50, 10–20.

Milota, M., Mosher, P., Li, K., 2007. VOC and HAP removal from dryer exhaust gas by absorption into ionic liquids. For. Prod. J. 57, 73–77.

Mitchell, C.S., Zhang, J., Sigsgaard, T., Jantunen, M., Lioy, P.J., Samson, R., Karol, M.H., 2007. Current state of the science: health effects and indoor environmental quality. Environ. Health Perspect. 115, 958–964.

Moser, B., Bodrogi, F., Eibl, G., Lechner, M., Rieder, J., Lirk, P., 2005. Mass spectrometric profile of exhaled breath—field study by PTR-MS. Respir. Physiol. Neurobiol. 145, 295–300. http://dx.doi.org/10.1016/j.resp.2004.02.002.

Myers, G.E., 1984. How mole ratio of UF resin affects formaldehyde emission and other properties : a literature critique. For. Prod. J. 34, 35–41.

Nazaroff, W.W., Weschler, C.J., 2004. Cleaning products and air fresheners: exposure to primary and secondary air pollutants. Atmos. Environ. 38, 2841–2865. http://dx.doi.org/10.1016/j.atmosenv.2004.02.040.

van Netten, C., Shirtliffe, C., Svec, J., 1989. Temperature and humidity dependence of formaldehyde release from selected building materials. Bull. Environ. Contam. Toxicol. 42, 558–565. http://dx.doi.org/10.1007/BF01700238.

Niedermayer, S., Fürhapper, C., Nagl, S., Polleres, S., Schober, K.P., 2013. VOC sorption and diffusion behavior of building materials. Eur. J. Wood Wood Prod. 71, 563–571. http://dx.doi.org/10.1007/s00107-013-0713-4.

Nielsen, K.F., 2003. Mycotoxin production by indoor molds. Fungal Genet. Biol. 39, 103–117. http://dx.doi.org/10.1016/S1087-1845(03)00026-4.

Nurzynski, J., 2015. Is thermal resistance correlated with sound insulation? In: 6th International Building Physics Conference, IBPC 2015. Energy Procedia. 78, pp. 152–157.
Nurzynski, J., 2008. The effect of additional thermal lining on the acoustic performance of a wall. In: Euronoise 2008, June 29–July 4.
Ohlmeyer, M., Makowski, M., Fried, H., Hasch, J., Schöler, M., 2008. Influence of panel thickness on the release of volatile organic compounds from OSB made of *Pinus sylvestris* L. For. Prod. J. 58, 65–70.
Osanyintola, O.F., Simonson, C.J., 2006. Moisture buffering capacity of hygroscopic building materials: experimental facilities and energy impact. Energy Build. 38 (10), 1270–1282.
Pacheco-Torgal, F., Jalali, S., Fucic, A., 2012. Toxicity of Building Materials. WP Woodhead Publishing, Cambridge.
Palumbo, M., Avellaneda, J., Lacasta, A.M., 2015a. Availability of crop by-products in Spain: new raw materials for natural thermal insulation. Resour. Conserv. Recycl. 99, 1–6.
Palumbo, M., Formosa, J., Lacasta, A.M., 2015b. Thermal degradation and fire behaviour of thermal insulation materials based on food crop by-products. Constr. Build. Mater. 79, 34–39.
Papadopoulos, A.M., 2005. State of the art in thermal insulation materials and aims for future developments. Energy Build. 37, 77–86.
Park, B.-D., Chang Kang, E., Yong Park, J., 2006. Effects of formaldehyde to urea mole ratio on thermal curing behavior of urea–formaldehyde resin and properties of particleboard. J. Appl. Polym. Sci. 101, 1787–1792. http://dx.doi.org/10.1002/app.23538.
Pasini, M., Berto, R., Brondino, M., Hall, R., Ortner, C., 2014. How to measure the restorative quality of environments: the PRS-11. Procedia Soc. Behav. Sci. 159, 293–297. http://dx.doi.org/10.1016/j.sbspro.2014.12.375.
Patkó, C., Patkó, I., Pásztory, Z., 2013. Indoor air quality testing in low energy wooden houses: measurement of formaldehyde and VOCs. Acta Polytech. Hung. 10, 105–116.
Petrič, M., 2013. Surface modification of wood. Rev. Adhes. Adhes. 1 (2), 216–247. http://dx.doi.org/10.7569/RAA.2013.097308.
Pinto, J., Paiva, A., Varum, H., Costa, A., Cruz, D., Pereira, S., Fernandes, L., Tavares, P., Agarwal, J., 2011. Corn's cob as a potential ecological thermal insulation material. Energy Build. 43, 1985–1990.
Pinto, J., Vieira, B., Pereira, H., Jacinto, C., Vilela, P., Paiva, A., Pereira, S., Cunha, V.M., Varum, H., 2012. Corn cob lightweight concrete for non-structural applications. Constr. Build. Mater. 34, 346–351.
Pirayesh, H., Khanjanzadeh, H., Salari, A., 2013. Effect of using walnut/almond shells on the physical, mechanical properties and formaldehyde emission of particleboard. Compos. Part B 45, 858–863. http://dx.doi.org/10.1016/j.compositesb.2012.05.008.
Pirayesh, H., Khazaeian, A., 2012. Using almond (*Prunus amygdalus* L.) shell as a biowaste resource in wood based composite. Compos. Part B 43, 1475–1479. http://dx.doi.org/10.1016/j.compositesb.2011.06.008.
Proietti, S., Desideri, U., Sdringola, P., Zepparelli, F., 2013. Carbon footprint of a reflective foil and comparison with other solutions for thermal insulation in building envelope. Appl. Energy 112, 843–855.
Qasass, R., Gorgolewski, M., Ge, H., 2014. Timber framing factors in Toronto residential house construction. Archit. Sci. Rev. 57 (3), 159–168.
Qin, M., Belarbi, R., Aït-Mokhtar, A., Allard, F., 2009. Simulation of coupled heat and moisture transfer in air-conditioned buildings. Autom. Constr. 18, 624–631.
Rahim, M., Douzane, O., Tran Le, A.D., Langlet, T., 2016. Effect of moisture and temperature on thermal properties of three bio-based materials. Constr. Build. Mater. 111, 119–127.

Ramesh, M., 2016. Kenaf (*Hibiscus cannabinus* L.) fibre based bio-materials: a review on processing and properties. Prog. Mater. Sci. 78–79, 1–92.
Ramesh, M., Alagisamy, P.S., Sakthivel, M., Mahalingam, A., Rao, B.V.A., 2013. A review of building acoustic materials. In: ACOUSTIS2013NEWDELHI, pp. 107–112.
Reitzig, M., Mohr, S., Heinzow, B., Knöppel, H., 1998. VOC emissions after building renovations: traditional and less common indoor air contaminants, potential sources, and reported health complaints. Indoor Air 8, 91–102. http://dx.doi.org/10.1111/j.1600-0668.1998.t01-2-00004.x.
Ricciardi, P., Belloni, E., Cotana, F., 2014. Innovative panels with recycled materials: thermal and acoustic performance and life cycle assessment. Appl. Energy 134, 150–162.
Rincón, L., Serrano, S., Cabeza, L.F., González, B., Navarro, A., Bosch, M., 2015. Experimental rammed earth prototypes in Mediterranean climate. In: Mileto, C., Vegas, F., Garcia, L., Cristini, V. (Eds.), Earthen Architecture: Past, Present and Future. CRC Press, Taylor & Francis Group, London, pp. 311–316.
Roffael, E., 2006. Volatile organic compounds and formaldehyde in nature, wood and wood based panels. Holz Roh Werkst. 64, 144–149. http://dx.doi.org/10.1007/s00107-005-0061-0.
Roffael, E., Dix, B., Okum, J., 2000. Use of spruce tannin as a binder in particleboards and medium density fiberboards (MDF). Holz Roh Werkst. 58, 301–305. http://dx.doi.org/10.1007/s001070050432.
Sahlberg, B., Gunnbjornsdottir, M., Soon, A., Jogi, R., Gislason, T., Wieslander, G., Janson, C., Norback, D., 2013. Airborne molds and bacteria, microbial volatile organic compounds (MVOC), plasticizers and formaldehyde in dwellings in three North European cities in relation to sick building syndrome (SBS). Sci. Total Environ. 444, 433–440. http://dx.doi.org/10.1016/j.scitotenv.2012.10.114.
Salata, F., Golasi, I., Vollaro, A.D.L., Vollaro, R.D.L., 2015. How high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study. Energy Build. 99, 32–49.
Salem, M.Z.M., Böhm, M., 2013. Understanding of formaldehyde emissions from solid wood: an overview. BioResources 8, 4775–4790. http://dx.doi.org/10.15376/biores.8.3.
Salem, M.Z.M., Böhm, M., Srba, J., Beránková, J., 2012. Evaluation of formaldehyde emission from different types of wood-based panels and flooring materials using different standard test methods. Build. Environ. 49, 86–96. http://dx.doi.org/10.1016/j.buildenv.2011.09.011.
Salonvaara, M., Ojanen, T., Holm, A., Kunzel, H., Karagiozis, A., 2004. Moisture buffering effects on indoor air quality – experimental and simulation results. In: Buildings IX, ASHRAE.
Salthammer, T., Mentese, S., Marutzky, R., 2010. Formaldehyde in the indoor environment. Chem. Rev. 110, 2536–2572. http://dx.doi.org/10.1021/cr800399g.
Schäfer, M., Roffael, E., 2000. On the formaldehyde release of wood. Holz Roh Werkst. 58, 259–264. http://dx.doi.org/10.1007/s001070050422.
Schripp, T., Langer, S., Salthammer, T., 2012. Interaction of ozone with wooden building products, treated wood samples and exotic wood species. Atmos. Environ. 54, 365–372. http://dx.doi.org/10.1016/j.atmosenv.2012.02.064.
Schwarzkopf, M., Huang, J., Li, K., 2010. A formaldehyde-free soy-based adhesive for making oriented strandboard. J. Adhes. 86, 352–364. http://dx.doi.org/10.1080/00218460903482549.
Secchi, S., Asdrubali, F., Cellai, G., Nannipieri, E., Rotili, A., Vannucchi, I., 2016. Experimental and environmental analysis of new sound-absorbing and insulating elements in recycled cardboard. J. Build. Eng. 5, 1–12.
Shea, A., Lawrence, M., Walker, P,., 2012. Hygrothermal performance of an experimental hemp-lime building. Constr. Build. Mater. 36, 270–275.
Shrubsole, C., 2015. Indoor Air Quality and Overheating: The Causes of Unintended Consequences [WWW Document]. URL https://www.gov.uk/government/uploads/

system/uploads/attachment_data/file/448184/ARCC-HCA-Clive-Shrubsole.pdf (accessed 25.05.16).
Shrubsole, C., Davies, M., Macmillan, A., May, N., 2014. 100 unintended consequences of policies to improve the energy efficiency of the UK housing stock. Indoor Built Environ. http://dx.doi.org/10.1177/1420326X14524586 (Special Issue).
Silva, S., Sabino, M., Fernandes, E., Correlo, V., Boesel, L., Reis, R., 2005. Cork: properties capabilities and applications. Int. Mater. Rev. 50 (6), 345–365.
Simões, T., McGregor, F., Fabbri, A., Faria, P., 2016. Contribution of hemp concrete for indoor passive moisture control. In: V FICAL – Fórum Ibérico da Cal, 23-25 Maio 2016, Lisboa, PT, pp. 307–316 (in Portuguese).
Simonson, C., Salonvaara, M., Ojanen, T., 2004a. Heat and mass transfer between indoor air and a permeable and hygroscopic building envelope: part I – field measurements. J. Therm. Envel. Build. Sci. 28 (1), 63–101.
Simonson, C.J., Salonvaara, M., Ojanen, T., 2004b. Moderating indoor conditions with hygroscopic building materials and outdoor ventilation. ASHRAE 110 (2), 804–819.
Sinha, A., Gupta, R., Kutnar, A., 2013. Sustainable development and green buildings. Drvna industrija 64 (1), 45–53. http://dx.doi.org/10.5552/drind.2013.1205.
Sobral, H.S. (Ed.), 1990. Vegetable plants and their fibres as building materials. In: Proceedings of the Second International RILEM Symposium, London.
Spengler, J.D., Sexton, K., 1983. Indoor air pollution: a public health perspective. Science 221, 9–17. http://dx.doi.org/10.1126/science.6857273.
Stazi, F., Tomassoni, E., Bonfigli, C., Di Perna, C., 2014. Energy, comfort and environmental assessment of different building envelope techniques in a Mediterranean climate with a hot dry summer. Appl. Energy 134, 176–196.
Stefanowski, B.K., Curling, S.F., Mansour, E., Ormondroyd, G.A., 2015. The sorption of volatile organic compounds (VOCs) by modified MDF panels and the effects on mould colonisation and growth. Presented at the International Panel Products Symposium, International Panel Products Symposium, Llandudno.
Stenman, H., 2008. Reed Construction in the Baltic Region Reports from Turku University of Applied Sciences, Estonia, Turku. ISBN: 978-952-216-037-9. 68 pp.
Suleiman, B., Larfeldt, N., Leckner, B., Gustavsson, M., 1999. Thermal conductivityand diffusivity of wood. Wood Sci. Technol. 33, 465–473.
Takagaki, A., Fukai, K., Nanjo, F., Hara, Y., 2000. Reactivity of green tea catechins with formaldehyde. J. Wood Sci. 46, 334–338. http://dx.doi.org/10.1007/BF00766227.
Terr, A.I., 2009. Sick building syndrome: is mould the cause? Med. Mycol. 47, S217–S222. http://dx.doi.org/10.1080/13693780802510216.
Trézl, L., Csiba, A., Juhász, S., Szentgyörgyi, M., Lombai, G., Hullán, L., Juhász, A., 1997. Endogenous formaldehyde level of foods and its biological significance. Z. Für Leb. Forsch. A 205, 300–304. http://dx.doi.org/10.1007/s002170050169.
Tyrväinen, L., Ojala, A., Korpela, K., Lanki, T., Tsunetsugu, Y., Kagawa, T., 2014. The influence of urban green environments on stress relief measures: a field experiment. J. Environ. Psychol. 38, 1–9. http://dx.doi.org/10.1016/j.jenvp.2013.12.005.
Verma, I., 2016. Use of wood in elderly care. In: Cronhjort, Y., Hughes, M., Paakkane, M., Sahi, K., Tukiainen, P., Tulamo, T., Vahtikari, K. (Eds.), Functional Wood. Aalto-yliopiston julkaisusarja CROSSOVER, 3/2016. Aalto University, Espoo, Helsinki, Finland. ISBN: 978-952-60-6871-8, pp. 70–73.
Viegas, C., Pinheiro, A.C., Sabino, R., Viegas, S., Brandão, J., Veríssimo, C., 2015. Environmental Mycology in Public Health: Fungi and Mycotoxins Risk Assessment and Management. Academic Press, Cambridge, MA.

Wall, K., Walker, P., Gross, C., White, C., Mander, T., 2012. Development and testing of a prototype straw bale house. Constr. Mater. 165 (CM6), 377–384.
Wang, D., Sun, X.S., 2002. Low density particleboard from wheat straw and corn pith. Ind. Crop Prod. 15, 43–50.
Weigl, M., Wimmer, R., Sykacek, E., Steinwender, M., 2009. Wood-borne formaldehyde varying with species, wood grade, and cambial age. For. Prod. J. 59, 88–92.
Weschler, C.J., 2004. Chemical reactions among indoor pollutants: what we've learned in the new millennium. Indoor Air 14, 184–194. http://dx.doi.org/10.1111/j.1600-0668.2004.00287.x.
WHO, 2009. WHO Guidelines for Indoor Air Quality: Dampness and Mould [WWW Document]. URL http://www.euro.who.int/__data/assets/pdf_file/0017/43325/E92645.pdf (accessed 17.10.16).
WHO, 2010. WHO Guidelines for Indoor Air Quality : Selected Pollutants [WWW Document]. URL http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf (accessed 18.05.16).
World Health Organization Regional Office for Europe, 2009. Who Guidelines for Indoor Air Quality: Dampness and Mould. World Health Organization, Copenhagen. http://dx.doi.org/10.1186/2041-1480-2-S2-I1, 228 pp.
Wolkoff, P., 2003. Trends in Europe to reduce the indoor air pollution of VOCs. Indoor Air 13, 5–11. http://dx.doi.org/10.1034/j.1600-0668.13.s.6.1.x.
Wolkoff, P., 1999. How to measure and evaluate volatile organic compound emissions from building products. A perspective. Sci. Total Environ. 227, 197–213. http://dx.doi.org/10.1016/S0048-9697(99)00019-4.
Wolkoff, P., Clausen, P.A., Jensen, B., Nielsen, G.D., Wilkins, C.K., 1997. Are we measuring the relevant indoor pollutants? Indoor Air 7, 92–106. http://dx.doi.org/10.1111/j.1600-0668.1997.t01-2-00003.x.
Xiong, J., Zhang, Y., 2010. Impact of temperature on the initial emittable concentration of formaldehyde in building materials: experimental observation. Indoor Air 20, 523–529. http://dx.doi.org/10.1111/j.1600-0668.2010.00675.x.
Yrieix, C., Dulaurent, A., Laffargue, C., Maupetit, F., Pacary, T., Uhde, E., 2010. Characterization of VOC and formaldehyde emissions from a wood based panel: results from an inter-laboratory comparison. Chemosphere 79, 414–419. http://dx.doi.org/10.1016/j.chemosphere.2010.01.062.
Yu, C.W.F., Kim, J.T., 2010. Building pathology investigation of sick buildings—VOC emissions. Indoor Built Environ. 19, 30–39. http://dx.doi.org/10.1177/1420326X09358799.
Yu, C.W.F., Kim, J.T., 2011. Long-term impact of formaldehyde and VOC emissions from wood-based products on indoor environments; and issues with recycled products. Indoor Built Environ. http://dx.doi.org/10.1177/1420326X11424330.
Yu, C.W.F., Kim, J.T., 2012. Long-term impact of formaldehyde and VOC emissions from wood-based products on indoor environments; and issues with recycled products. Indoor Built Environ. 21, 137–149. http://dx.doi.org/10.1177/1420326X11424330.
Zach, J., Hroudová, J., Brožovský, J., Krejza, Z., Gailius, A., 2013. Development of thermal insulating materials on natural base for thermal insulation systems. In: 11th International Conference on Modern Building Materials, Structures and Techniques, MBMST 2013. Procedia Eng. 57, pp. 1288–1294.
Zhang, J. (Jim), Smith, K.R., 2003. Indoor air pollution: a global health concern. Br. Med. Bull. 68, 209–225. http://dx.doi.org/10.1093/bmb/ldg029.
Zhu, X., Kim, B.-J., Wang, Q., Wu, Q., 2014. Recent advances in the sound insulation properties of bio-based materials. BioResources 9 (1), 1764–1786.

This page intentionally left blank

Test methods for bio-based building materials

7

7.1 Introduction

S. Curling
Bangor University, Bangor, United Kingdom

Bio-based materials, like all materials, are likely to experience a range of environments and challenges that can affect the performance of the material, such as the effects of weathering and moisture. In addition, as bio-based materials are organic in their nature, this means that they are likely to be susceptible to attack by natural organisms ranging from bacteria and fungi up to insects and higher animals. When developing new materials and testing existing materials for suitability for specific uses, the material ultimately has to be tested against specific environments or organisms. Service and performance data – how well a product performs in use – are critical and essential. However, commercial and legislative pressures make performance testing essential during product development. There is a need for a range of differing test methods to ensure material performance is tested under the widest range of environments and challenges as possible.

This chapter discusses the different types of tests used to measure performance against the wide range of environments and challenges that bio-based materials may encounter. The types of environments that bio-based materials can be exposed to are categorised by hazard or use classes, broadly labelled 1–5, with the higher classes having a higher biological challenge. Differing regulatory bodies may have other subdivisions. Based on the situation a product is exposed to will determine the types of risk and therefore the minimum testing required for approval of a product for use in that environment (Table 7.1).

The testing approach can be separated into three categories:

- Laboratory testing: Ideal for screening and comparing material performance under controlled conditions. These are generally the quickest types of test.
- Field testing: Testing of promising materials in a controlled and replicable manner, but in conditions more representative of real-world environments. These are generally longer-term tests.
- Service life testing and monitoring: Once a material has been installed or used, it should be monitored to ensure good performance and safety.

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00007-0
© 2017 Elsevier Ltd. All rights reserved.

Table 7.1 **Hazard classes and suggested testing regimes for product approval for use in noted conditions**

Hazard class	**1**	**2**	**3**	**4**	**5**
Service conditions	**Interior, dry**	**Interior, or undercover, not exposed to the weather. Possibility of water condensation**	**Exterior, above ground, exposed to the weather**	**Exterior in-ground contact and/or fresh water**	**Permanently or regularly submerged in salt water**
Mould/stain fungal test	✓	✓	✓	✓	–
Basidiomycete fungal test	–	✓	✓	✓	✓
Soft rot test	–	–	–	✓	✓
Borers test	✓	✓	✓	✓	–
Termite test[a]	–	✓	✓	✓	–
Marine borer test	–	–	–	–	✓
Field test	–	–	L-Joint[b]	Stake test[b]	Marine test

[a] Termite test required in areas where termites are present.
[b] Optional but recommended.
Compiled from EN 335-1 (CEN, 2006a), HSE (2001) and AWPC (2015).

7.2 Laboratory testing

Throughout history, one biomaterial that has seen ubiquitous use is wood. It is therefore no surprise that many methods have been developed for testing the durability of and effectiveness of preservation systems for wood. Many of these tests have been used or modified for use with other natural materials.

7.2.1 Bacteria, moulds and decay fungi

S. Curling, L.R. Gobakken†*
*Bangor University, Bangor, United Kingdom
†Norwegian Institute of Bioeconomy Research (NIBIO), Oslo, Norway

7.2.1.1 Basidiomycete decay fungi

When dealing with micro-organisms, basidiomycete decay fungi, causing brown or white rot, are responsible for the greatest structural changes to timber and are therefore of greatest concern for structural bio-based materials. This type of decay is prevalent in both above- and in-ground contact situations.

The main approach in laboratory testing of durability or preservative efficacy has been to assess performance of specimens exposed to fungal monocultures. Two basic systems of fungal exposure have been used: (1) soil block methods and (2) agar block methods. In soil block tests, small samples of the material are exposed to pure cultures of basidiomycetes growing on wooden feeder blocks over sterile natural soil (Behr, 1972; Lea and Bravery, 1986; Bravery and Lea, 1987; BS, 1990). In the agar block test, samples are exposed on an agar medium (Willeitner, 1965; Savory, 1969; Lea, 1982). A partial list of common test methods is given in Table 7.2.

The tests are generally performed in glass or plastic jars (Figs 7.1 and 7.2) with each jar having one fungal monoculture and one or two sample blocks (depending on sample size or test method). Modifications on the basic method have also been used, for example, the mini-block test that is a rapid test using smaller test samples than normal (Bravery, 1979) or the terrestrial microcosm test that uses a soil burial system on a small scale (Nilsson and Edlund, 1995; Edlund and Nilsson, 1998). Vermiculite overlays have been used in both soil and agar block tests (e.g. BS 1982 (BS, 1990); Kerner-Gang, 1987) to maintain conditions such as high moisture content (*MC*). As MC is so critical, alternative methods have been developed to determine critical MCs for decay (Meyer and Brischke, 2015; Meyer *et al.*, 2015)

Both soil block or agar block test systems use mass loss of the material compared with controls as the test criteria. This does raise the risk of fungal strain variation, and although specific test strains and cultures are specified, virulence controls that must show a specified level of weight loss are included to test validity.

Whichever method is preferred, it needs to be understood that both forms rely on standardised conditions for moisture, temperature, light and lack of competition for the decay organism and therefore provide optimal conditions for growth and attack by the

Table 7.2 Common test methods used for decay fungi

Method	Title
ASTM D1413-99 (ASTM, 1999)	Method for Wood Preservatives by Laboratory Soil-Block Cultures
BS 1982-0-3 (BS, 1990)	Fungal Resistance of Panel Products Made of or Containing Materials of Organic Origin
EN 113:1996/A1 (CEN, 1996)	Wood Preservatives – Test Method for Determining the Protective Effectiveness Against Wood Destroying Basidiomycetes – Determination of the Toxic Values
ENV 839 (ENV, 2014)	Wood Preservatives – Determination of the Protective Effectiveness Against Wood Destroying Basidiomycetes. Application by Surface Treatments
ENV 12038 (ENV, 2002)	Durability of Wood and Wood-Based Products – Wood-Based Panels – Method of Test for Determining the Resistance Against Wood-Destroying Basidiomycetes
CEN/TS 15083-1 (CEN, 2005c)	Durability of Wood and Wood-Based Products – Determination of the Natural Durability of Solid Wood Against Wood-Destroying Fungi. Test Methods – Part 1: Basidiomycetes
CEN/TS 15083-2 (CEN, 2005d)	Durability of Wood and Wood Based Products – Determination of the Natural Durability of Solid Wood Against Wood-Destroying Fungi. Test Methods – Part 2: Soft Rotting Micro-Fungi

Fig. 7.1 Racks of sample jars containing fungi and samples in a conditioning room.

organism. This therefore provides a very stringent test for materials and preservatives and may be thought of as the worse-case scenario. However, the nature of these tests does raise concerns when testing new methods of wood treatment – namely, modified wood. Wood can be modified by heat or chemical treatments, such as acetylation or furfurylation. One of the protective measures these methods provide is changing

Fig. 7.2 ENV 12038 (ENV, 2002) testing of chipboard against white rot fungi. The sample is placed on to an inert support (either glass, metal or plastic) to stop waterlogging of the sample from too high a level of water sorption.

the moisture sorption properties of the wood, which can be an effective method of preventing wood decay. However, in a standard wood decay test, the levels of moisture are very high, and this may negate the advantage the treatment methods provide (Ormondroyd *et al.*, 2015). At the time of writing, methods such as EN 113 (CEN, 1996) are still the routine test for modified wood. CEN/TS 15083-1 (CEN, 2005c) and EN 113 (CEN, 1996) both aim to determine the natural durability of a timber against wood-destroying basidiomycetes cultured on an agar medium. Gellerich *et al.* (2015) summarised the main differences between the two tests and performed both tests on matching samples to seek out any differences and concluded that the durability classification showed similar results for both calculations/standards.

In terms of structural materials, there is also the concern that mass loss may not be the ideal test criteria, with strength properties being far more critical. Test methods such as EN 113 (CEN, 1996) rate mass losses of 3% as inconsequential. However, it has been shown (Curling *et al.*, 2002a) that even at a mass loss less than 5%, strength properties such as work to maximum load, modulus of rupture (*MOR*) and modulus of elasticity (*MOE*) can be reduced by up to 80%, 40% and 20%, respectively – in other words, significant strength reductions. Strength tests have been used to assess fungal decay (e.g. Deppe and Gersonde, 1977; Sexton *et al.*, 1993; Imamura, 1993, 1994; Curling *et al.*, 2002b), but these also offer challenges, for example, strength tests require larger sample sizes (and more replicates) (McNatt, 1984) making the practicalities for fungal exposure more difficult. An alternative may be dynamic mechanical thermal analysis that has been used for wood decay studies (Birkinshaw *et al.*, 1999) but has not yet been utilised fully. Therefore, at the time of writing, most standard test methods use mass loss as the test criteria.

Wood-based panel materials are tested in a similar method to solid wood, for example, ENV 12038 (ENV, 2002), via exposure to fungal monocultures. One particular challenge with panels is the resin used. Various studies (Savory, 1969; Willeitner, 1965; Hedley, 1983; Deppe, 1987; Kerner-Gang, 1987) showed that leached boards gave

higher dry weight losses than unleached boards during decay tests and that unleached boards also showed inhibition of the fungus within the culture vessels. It has been concluded that this is due to volatile formaldehyde being liberated from the material. However, this inhibitory effect, caused by the release of formaldehyde in test, does not reflect the behaviour of the boards in service (Cockroft, 1973; Deppe, 1987) but can have significant effects on durability ratings derived from laboratory tests. When testing boards and the boards cannot be left to age (Curling and Murphy, 1999), the tests such as ENV 12038 (ENV, 2002) use a preconditioning step prior to fungal exposure, in order to reduce the impact of the volatiles. This preconditioning may involve a leaching method based on EN 84 or the use of a vacuum oven based on EN 73 (CEN, 2014a) (Curling and Murphy, 1999). Leaching, in particular, may have serious impacts on board materials due to swelling. Using a mass loss system for wood panels also has the further disadvantage in that a simple physical deterioration of the adhesive bond may result in significant loss of strength without significant dry weight loss (Dinwoodie, 1978).

Other test criteria for fungal decay have also been used.

Immunodiagnosis using mono- and polyclonal antibodies has been developed to detect incipient decay (Clausen *et al.,* 1991) although on its own it is a method for detecting the presence rather than extent of decay. Decay fungi may be present without significant decay occurring, and therefore, an alternative test would be needed to determine the progression of the decay (Clausen and Kartal, 2003).

Near infrared (*NIR*) has also been used to assess wood decay and is a promising approach (Fackler *et al.*, 2006; Green *et al.*, 2010; Sandak *et al.*, 2010). It uses NIR to detect the changes in the cellulosic, hemicellulosic and lignin elements of wood, which begin with incipient decay (Curling *et al.*, 2002b) and progress with advancing decay.

Acoustic and vibrational methods have also been used. Acoustic methods are more commonly used in standing trees and large wooden members, but the technique has been used at small laboratory scale (Machek *et al.*, 2001; Alfredsen and Larnøy, 2006) and showed good correlation to strength properties such as MOE, which can then be correlated to the level of decay. Ross *et al.* (1997) showed a good correlation between stress wave characteristics and compressive strength.

7.2.1.2 Soft rot decay

Soft rot is generally caused by ascomycete fungi and generally affects materials in ground contact. It can cause significant damage in this environment, and there are a number of laboratory methods based around soil bed systems, where samples or stakes are placed into active soils under controlled condition, for example, ENV 807 (ENV, 2001) and CEN/TS 15083-2 (CEN, 2005d). ENV 807 (ENV, 2001) does include two versions of testing, with part 2 being a soil bed test using unsterile soil with a test period of up to 32 weeks. Part 1 however uses a vermiculite (a type of expanded mica) burial system where the vermiculite is inoculated with a selected soft rot fungi mixture. The soil bed system has been shown to be variable in results obtained (Herring *et al.*, 1997) mainly due to differing soil characteristics. The results obtained from the two test systems, soil bed and vermiculite, with similar samples have also been shown to not be highly comparable (Herring *et al.*, 1997). However, the soil bed test may be considered to give a more accurate picture of the performance of the materials.

Table 7.3 Common test methods for mould and stain fungi

Method reference number	Title
ASTM D2574 (ASTM, 2016)	Resistance of Emulsion Paints in the Container to Attack by Micro-Organisms
ASTM D3273 (ASTM, 2011a)	Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber
ASTM D4445 (ASTM, 2015)	Fungicides for Controlling Sapstain and Mold on Unseasoned Lumber (Laboratory Method)
ASTM D5590 (ASTM, 2010)	Determining the Resistance of Paint Films and Related Coatings to Fungal Defacement by Accelerated Four-Week Agar Plate Assay
BS EN ISO 846 (CEN, 1997b)	Plastics: Evaluation of the Action of Microorganisms
BS 3900-G6 (BS, 1989)	Methods of Test for Paints. Assessment of Resistance to Fungal Growth
EN 152 (CEN, 2011)	Wood Preservatives. Determination of the Protective Effectiveness of a Preservative Treatment Against Blue Stain in Wood in Service. Laboratory Method
EN 15457 (CEN, 2014d)	Paints and Varnishes. Laboratory Method for Testing the Efficacy of Film Preservatives in a Coating Against Fungi
NT Build 338 (Nordtest, 1989)	Coatings: Mould Resistance

7.2.1.3 Mould and blue-stain fungi

Mould fungi, although they cause little structural damage (Schmidt, 2006), are a cause of significant aesthetic and health problems in buildings (Nielsen, 2003; Jarvis and Miller, 2005). Therefore, there has been considerable interest in testing materials and products either for their susceptibility to or their effectiveness against these types of fungi. A partial list is given in Table 7.3.

In general, these methods use small-scale samples, either wood discs or paper filter discs with an active ingredient, inoculated with a spore suspension of selected mould fungi, with incubation carried out at standardised temperatures and humidity, that is, ideal conditions. This approach is ideal for testing ultimate susceptibility or the effectiveness of control products but may not give any information on growth in marginal conditions. A number of the test methods are suited for testing coatings (ASTM D3273, ASTM, 2011a) or plastics (ISO 846) and therefore have not been optimised for testing novel bio-based building materials. Assessment is generally based on visual assessment criteria. The visual criteria are based on an estimation of growth, usually as a percentage of the total surface area of the material (Fig. 7.3). Some methods use microscopy to determine the initial low levels of growth. Whilst visual assessment is suitable for solid materials, there are issues when looking at low density porous or fibrous materials.

Mould growth is heavily dependent on humidity and temperature and many methods attempt to model and test the effects. Several mould growth models exist where some are based on stable climate conditions (Adan, 1994; Ayerst, 1969; Hukka and Viitanen, 1999; Johansson *et al.*, 2010; Krus *et al.*, 2007; Sedlbauer, 2001) whilst

Fig. 7.3 Mould growth on wood-based panel material under laboratory test conditions showing significant colonisation.

Fig. 7.4 *Left*: Application of spore suspension on wood wafer. *Right*: Mould growth on wood wafer.

others use ambient climatic parameters (Gobakken *et al.*, 2010; Thelanderson and Isaksson, 2013). Fluctuating conditions were tested by Pasanen *et al.* (2000) and showed differences in mould growth depending on the source of moisture, for example, capillary action or condensation and vapour sorption. Methods have been developed to model mould growth limits based on the humidity and temperature such as that detailed by Viitanen and Ritschkoff (1991) or the isopleth test (Sedlbauer, 2001). These tests develop models that give probabilities of mould risk at varying humidity and temperature ranges for a specific material.

Many of the existing tests were designed for wood-based systems or for coating systems. Other non-standard tests have been developed, such as modified versions of standard tests (Gobakken and Alfredsen, 2016) (Fig. 7.4) or the Mycology test (Blom and Bergstrom, 2005). The introduction of bio-based construction materials has led to the development of further novel testing strategies (Hoang *et al.*, 2009; Stefanowski *et al.*, 2015; Stefanowski *et al.*, 2017) although many of these are still being optimised.

7.2.1.4 Bacteria

Bacteria can cause deterioration of wood-based materials in ground contact by increasing permeability and altering the material structure. Some species are also able

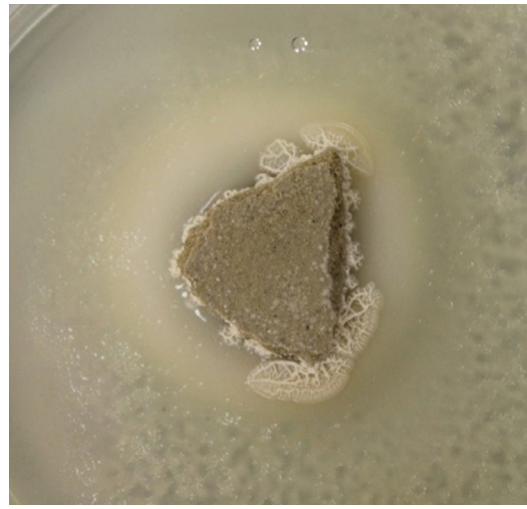


Fig. 7.5 Bacterial growth testing on a plaster-based building material according to ISO 846.

to break down traditional wood preservatives under certain conditions allowing other organisms, such as decay fungi, to cause further decay (Clausen, 1996). In terms of traditional construction materials, they do relatively little damage so laboratory methods are not as common as for other materials. ISO 846 is a testing method for plastic materials using both mould fungi and bacteria (Fig. 7.5) and so has been used to test materials in pure culture. Generally, bacterial biodeterioration has been tested in soil bed or soil burial systems along with soft rot fungi.

7.2.1.5 Combination tests

As noted above, bacterial tests have been conducted in soil bed tests in conjunction with soft rot fungi test. As these are unsterile tests, they are laboratory simulations of field tests, using controlled conditions of temperature, moisture, humidity and soil type. Although these methods take more time than other laboratory tests, they may be applicable to real-life situations. In real-world situations, the ecology of biodeterioration is important, for example, as noted bacterial decay can increase the susceptibility of wood-based materials to decay fungi (Clausen, 1996). It has been found that in some cases mould fungi can increase the susceptibility of materials to soft rot fungi (Herring and Dickinson, 1999). To accompany mechanical, hygric and photochemical preconditioning, biological conditioning has also been suggested (Molnar *et al.*, 1996, 1997) as a precursor to traditional decay tests. These tests showed reduced effectiveness of preservatives in decay tests following the biological preconditioning.

7.2.1.6 Interpretation and evaluation of test data

There is a large amount of data on the durability of solid wood in service, making it relatively easy to contrast laboratory data with the service data from different use classes. These tests optimise conditions for the fungus (Jackson and Savory, 1968),

and so test results will give comparative indications of durability, not absolute values. In order to aid the interpretation of results, materials can be tested in conjunction with a specific reference timber (Jackson and Savory, 1968; Hedley, 1983). If the material performs at least as well, or better than the reference timber, the material can be considered suitable for a similar end use. Construction materials come in a range of sizes and shapes, and under test conditions, thinner materials may show greater decay than thicker materials of the same type, due to the material composition and the surface-to-volume ratio difference. When interpreting the data from laboratory tests, it is therefore important to understand the limitations of the test and what information the data provides. For example, as previously noted, the normal decay test for wood materials may not be a suitable predictor of how well-modified wood will perform due to the harshness of the test (Ormondroyd *et al.*, 2015).

7.2.1.7 Development of testing methods for biobased materials

Many of the methods discussed have been developed for use with wood or wood-based materials. The question is then whether these methods are suitable for non-wood materials. Logically, they should be suitable for non-wood lignocellulosic materials such as bamboo, bagasse or hemp, and mass loss decay tests are indeed used for panel-type materials constructed using these materials. However, bio-based materials are used in other applications such as insulation where standard decay tests may not be suitable (Curling *et al.*, 2015). Another question for construction materials is in synergistic interactions – for example, could a bio-based insulation material have a positive or a negative effect on the susceptibility of other structural components to be attacked by fungi? These interactions can be modelled if the relevant information is known (Stefanowski *et al.*, 2015). For many novel materials, however, this information is not readily available, and therefore, testing is required. Initially, laboratory tests are the ideal screening method to determine material characteristics, and therefore, laboratory-based tests will continue to be an important tool in material characterisation.

7.2.2 Insects

S. Curling
Bangor University, Bangor, United Kingdom

Bio-based materials are also susceptible to be attacked and damaged (often serious damage) by a range of insects suited to varying environments. Exact risks of attack are often country- or region-specific, and whilst most testing methods share similar procedures, many are optimised for specific local challenges.

7.2.2.1 Subterranean termites

The general approach when testing natural materials, especially wood, to the action of termites is predicated to testing chemicals used as preservatives. All methods involve exposing the material to live insects under controlled conditions, although in

different parts of the world, differing species are considered important. In Europe, standards stipulate the use of *Reticulitermes flavipes* as the test insect (although other species of the family Rhinotermitidae can be included) and Australian standards favour *Coptotermes acinaciformis* or *Mastotermes darwiniensis*, whilst American standards state that the common species of the region should be studied. As the tests are designed for preservative testing, accelerated ageing techniques, such as leaching (EN 84) and evaporative ageing (EN 73, CEN, 2014a), may be used before testing.

In Europe, two standard approaches are used – determination of the toxic values of a preservative (EN 117, CEN, 2012a) and determination of the preventative action (EN 118, CEN, 2013a) of preservative chemicals. The method used in EN 117 (CEN, 2012a) defines the concentration at which a product completely prevents attack by the test insect in impregnated wood of a susceptible wood species. The test is performed in glass/plastic containers half-filled with a matrix such as moistened sand with a support ring placed on top. Termites, mostly workers, are introduced into the container and observed to check viability before the test block is introduced. Blocks are exposed for 8 weeks at 26°C, after which the viability of the insects is checked and the blocks evaluated on a scale scoring 0, for no attack, and up to 4, for strong attack, that is, erosion over more than 10% of the surface area or penetration deeper than 3 mm into the blocks. Results of treated blocks are compared with untreated controls. The American standard ASTM D3345 (ASTM, 2011b) uses a similar test assembly but in evaluation determines the presence of tunnels, position of termites in relation to the blocks and mortality of the termites and also evaluates the blocks on a scale of 10 (no attack apart from surface nibbling) to 0 (failure), as described in Table 7.4. Mass loss and final condition (mortality) of the test termites are also used in the evaluation.

The EN 118 (CEN, 2013a) standard is used to determine any preventative action against termites by chemical surface treatments. In this method, a vertical glass tube is glued at the base to a flat wood test specimen that has been surface coated with the preservative under test. The tube is filled with a matrix similar to that in EN 117 (CEN, 2012a) and termites are added. Incubation is for 8 weeks, after which the adhesive at the base of the tube is broken to expose the treated surface of the specimen. Termite damage to the specimen surface is rated on the 0–4 scale as in EN 117 (CEN, 2012a). Mass loss can also be used as part of the evaluation. The Australian test, using a similar exposure method, has a matrix-filled glass vessel with a specimen exposed to termites for a set time (AWPC, 2015) and relies mainly on the mass loss caused by the termites as the assessment criteria.

All the above test methods are examples of 'no-choice' methods, where the test block is the only food source for the termites. An American standard, AWPA E1-97 (AWPA, 2016),

Table 7.4 Damage rating of wood specimens from termite feeding based on ASTM/AWPA methodology

Rating	Description
10	Sound or trace attack
9	Light attack
7	Moderate attack, penetration
4	Heavy attack
0	Failure

introduces the 'two-choice' method. The basic assembly is the same for the abovementioned tests, but both a treated and an untreated test block are placed in the vessel – the termite therefore has the choice between the two. This method tests whether the chemical is able to prevent or deter feeding if other food sources are available, which in real-life situations there may well be. Assessment is by the 1–10 scale and mass loss.

7.2.2.2 *Lyctid (powderpost) beetle borers*

The European standard EN 20 (CEN, 1992a) describes a method to test the action of chemicals against *Lyctus brunneus* using application either by a surface treatment (Part 1, CEN, 1992a) or by impregnation (Part 2, CEN, 1993a). The basic method, also shared by Australian tests (AWPC, 2015), uses single specimens, treated by either method, placed in test containers into which male and female adult beetles are introduced. The test ends when larvae in the untreated control specimens have emerged as adults, which is normally 12–16 weeks after exposure to egg laying. At the end of the test, the specimens are split and visually assessed for larval tunnelling and exit holes. At an earlier stage, X-ray imaging (Cymorek, 1977) could be used to detect tunnelling. The toxic threshold concentration required to inhibit total larvae development is deemed to be a concentration between the highest retention where tunnelling is seen and the lowest retention where tunnelling is not seen. Previous research (Peters *et al.*, 2002) in Australia also involved characterising the wood samples for both starch content and pore size. Samples with pore sizes smaller than 90 µm were deemed resistant to attack. The assessment method used for attack utilised a rating of susceptible (S) to non-susceptible (*NS*) with the susceptible rating broken down further on a subrating of S1–S3 as shown in Table 7.5.

To test wood veneers and panel products, similar test methods to the above have been used (Cymorek, 1977), although in the case of thin veneers bundles of multiple veneers were bound together to form a block for the beetles to infest.

7.2.2.3 Anobium punctatum *(common furniture beetle)*

Test methods for *A. punctatum* correspond to two differing situations: preventative tests to stop infestation and curative to kill off larvae already within the wood. Preventative tests take two forms corresponding to the different life cycle stages of the beetle. To replicate larval transfer (e.g. sound wood placed next to infested wood), European (EN 21, CEN, 1988) and Australian (AWPC, 2015) methods involve placing larvae into predrilled holes in fully impregnated Scots pine sapwood test. At the end of

Table 7.5 Rating scheme for powderpost beetle attack (Peters *et al.*, 2002)

Rating	Description
NS	Non-susceptible
S1	Slightly susceptible; attack confined to short larval channels along the vessel
S2	Moderately susceptible; moderate amount of larval channelling
S3	Highly susceptible; complete destruction of the sapwood with broad, frass-packed larval galleries

6 months, the test is assessed by splitting the wood and determining whether the larvae have survived and grown (increased in weight).

To replicate the situation where adults lay eggs on wood, methods such as EN 49-1 (CEN, 2016d) or EN 49-2 (CEN, 2015a) based on preservative treatment type) introduce adults to wood, allowing eggs to be deposited. Any subsequent hatching and larval boring is then assessed after 6 months' incubation. Toxic thresholds are determined where the preservative stops hatching entirely or allows hatching but stops larval development.

Curative testing procedures such as that described in EN 48 (CEN, 2005a) determine the lethal effect of a surface treatment on larvae already present in the wood. In this test, larvae are introduced into predrilled holes in the transverse faces of wood (e.g. Scots pine) blocks that are then sealed when tunnelling is established. The test preservative is then brushed or spread on to the longitudinal surfaces of the specimen, and the uptake is determined. Assessment is based on the number of living/dead larvae after 8 weeks for fast-acting treatments or 16 weeks for slow-acting treatments. In a similar manner, EN 370 (CEN, 1993b) tests the ability of a curative application to stop the emergence of adult beetles (thus preventing spread).

7.2.2.4 Hylotrupes bajulus *(longhorn beetle)*

In a similar way as to testing for *A. punctatum*, European standards for testing preservatives against *H. bajulus* test differing stages of the beetle's life cycle. European Standard EN 47 (CEN, 2016c), for example, uses different categories of larvae: those up to 3 days old after hatching and optionally larger, older larvae. Larvae are placed into holes drilled into the surfaces of treated wood blocks, the holes sealed and the assembly incubated for between 12 and 48 weeks. Assessment is based on larval activity in the cut blocks with toxic values determined by concentrations at which the larvae are living or dead.

Surface treatments of wood are tested using the method described in the European standard EN 46 (CEN, 2016a,b) that determines the ability of larvae to tunnel through treated surface layers to reach unprotected interior wood. As the beetles generally lay eggs in cracks in wooden surfaces, a glass plate is placed over the specimen leaving a narrow gap into which larvae are inserted. The test is assessed after 12 weeks with the toxic values determined as the lowest concentration where all larvae are dead and the next lowest concentration in blocks where live larvae are found.

Eradicant action of preservatives against *H. bajulus* can be tested using European standard EN 1390 (CEN, 2006c) (previously EN 22, CEN, 1974) where larvae are inserted into holes in wood and allowed to establish. After three months, the holes are sealed and the treatment applied; fast treatments are exposed for 12 weeks and slow treatments for 24 weeks. The numbers of larvae that are dead or moribund, living or undergoing pupation, are then determined. Some researches recommend longer test periods (up to 12 months) to account for larval fasting intervals (Graf *et al.*, 1998).

7.2.2.5 Tineola bisselliella *(clothes moth) and* Anthrenus flavipes *(carpet beetle)*

The use of alternative bio-based materials, such as wool fibre, in insulation and other building materials raises the risk of attack by insects not normally considered a problem for construction materials; for example, the clothes moth *T. bisselliella* or the carpet

beetle *A. flavipes*. Materials can be tested against these insects using a standard method defined by ISO 3998 (ISO, 1977). Larvae of the test species are placed onto discs of the test material placed in petri dishes and incubated for 14 days in darkness and under controlled temperature and humidity. The materials are assessed in terms of damage visible to the eye and by mass loss. Long-term tests lasting up to 6 months and using a mixture of egg, larval and adult beetle tests can also be employed (EOTA, 2015).

7.2.3 Marine borers

S.M. Cragg
University of Portsmouth, Portsmouth, United Kingdom

7.2.3.1 Major marine borer types

Though the capability for effective lignocellulose breakdown is rare, it is known from a diversity of organisms from across the tree of life. In coastal construction, the fungi and insects that are a threat to land-based wooden structures should be considered a threat to the above water portions. In the submerged portion of structures and in marine environment in general, there are bacteria and fungi capable of degradation of wood cell walls, but the rate of degradation is slow and so is generally only significant over the exposure time spans of archaeological timbers (Björdal, 2012). Timbers exposed in marine environments are, however, subject to rapid degradation by wood-boring invertebrates (Fig. 7.6).

In the high intertidal, the wharf borer *Nacerdes melanura* exploits decaying wood (Pitman *et al.*, 2003). Reports of this borer from Kansas indicate that it is not restricted to the marine environment! A wood-boring weevil, *Pselactus spadix*, is widespread around the coast of the United Kingdom in decayed timbers in the high intertidal (Oevering *et al.*, 2001). Its wider range has yet to be defined, but the lack of reports of substantial damage indicates that from the point of view of wood protection, it is not a priority.

Threats to submerged portions of wooden structures and boats are predominantly from crustaceans and bivalves, and testing protocols reflect this. The crustaceans that cause economically significant damage are amphipods from the family Cheluridae and isopods from the families Limnoriidae and Sphaeromatidae. The bivalves are from the related families Teredinidae, Pholadidae and Xylophagaidae (Distel *et al.*, 2011; Voight, 2015).

Chelurids are temperate and tropical amphipod crustaceans almost always found in association with colonies of limnoriids, whose tunnels they enlarge (Coleman and Renz, 2009). Sphaeromatids are locally important in coastal tropical and subtropical waters especially, but not exclusively, in low salinity estuarine conditions (Cragg, 2003). Their tunnelling activity is restricted to the intertidal zone, and hence, field trials in which the test materials are suspended from floating structures or which are placed subtidally do not evaluate the resistance of these materials to sphaeromatids. Wood heavily treated with *CCA* has been known to rapidly fail to sphaeromatids (Cragg, 1988). The ability to tunnel into wood treated with broad-spectrum biocides seems to be due to only very limited ingestion of the wood. In fact, these borers have been shown to feed by using the brush setae on their walking legs to filter phytoplankton

Fig. 7.6 Structure in Portsmouth, the United Kingdom, damaged by limnoriid attack in the intertidal zone.

from the water current generated within their tunnels by beating of hind limbs, the pleopods (Si *et al.*, 2002).

Limnoriids are less tolerant of low salinities, but in marine salinities are prevalent in wood in the low intertidal and subtidal from the periphery of polar regions to the tropics, with some reported from the deep sea. Some limnoriids attack seaweeds or seagrasses rather than wood. The main pest species are reported to be *Limnoria lignorum* from cold-temperate boreal waters; *Limnoria quadripunctata* (Fig. 7.7), which is invasive in cool- to warm-temperate waters North and South of the equator; and *Limnoria tripunctata*, which is cosmopolitan in warm-temperate to tropical waters.

The pholad borers are tropical and in some cases, for example, *Lignopholas*, tolerant of low salinities. The most destructive species is *Martesia striata*, which attacks other materials including brickwork and plastic as well as wood (Jenner *et al.*, 2003). It is active from the low intertidal and below. Like the wood tunnelling species of *Sphaeroma*, it is economically significant in certain restricted areas, and the reason for the existence of these hot spots of activity by these borers has not been discovered. Again, like *Sphaeroma*, this animal filter feeds and so does not ingest the wood fragments generated during tunnelling. Xylophagaids are wood consumers mainly found in waters so deep that any degradation of wood is of ecological rather

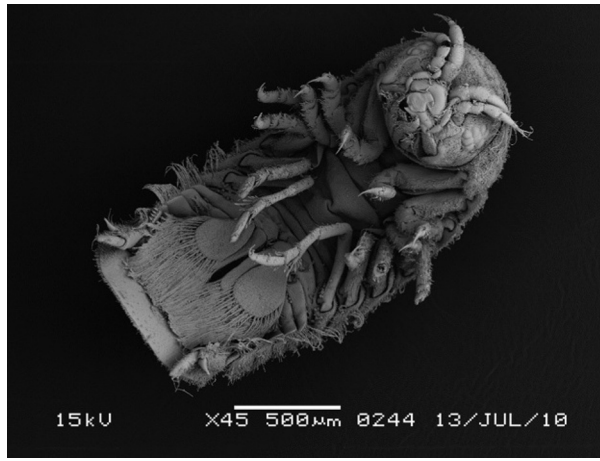


Fig. 7.7 Scanning electron microscope image of *Limnoria quadripunctata*.

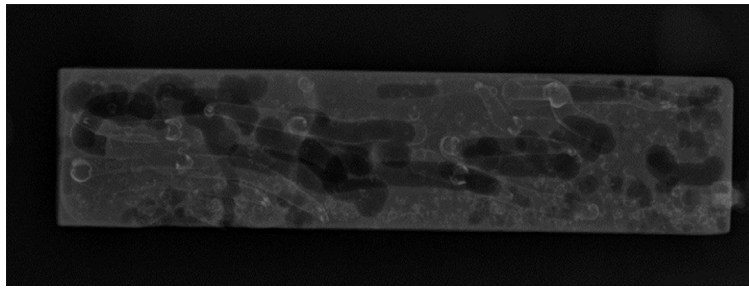


Fig. 7.8 X-ray of a panel heavily tunnelled by teredinid borers. This would be rated 4 in the EN 275 (CEN, 1992b) scheme.

than economic significance (Voight, 2015), though commercially significant damage to lobster pots placed on the outer continental shelf of the NE United States has been reported (Dealteris *et al.*, 1988).

Teredinids are also wood consumers, which are widespread and prevalent from cold-temperate to tropical waters and from brackish to oceanic waters. These are the principal threat to wooden construction in the sea (Fig. 7.8), but limnoriids are also capable of causing hugely expensive damage.

7.2.3.2 Rationale of laboratory testing with marine borers

An extreme example of the potential severity of attack by combinations of marine borers is provided by the extensive study of the wharves constructed using untreated timber around the coast of New Guinea from 1941 to 1945. The engineers estimated that these structures became unserviceable within 18 months of installation (Shillinglaw and Moore, 1947). There are numerous other examples from around the world of costly failure after a too-short service life. Laboratory tests fit into the continuum of

evaluation that ranges from cheap and rapid to expensive and long term. The continuum consists of initial screening, critical laboratory testing, field (=marine) tests and service trials, such as that reported on by Shillinglaw and Moore.

Innovation in wood protection in the marine environment is urgently needed. This is partly because the use of well-established and generally effective preservatives for marine use such as chromated copper arsenate (CCA) and creosote is now restricted or prohibited in many countries due to legislation (European Commission, 2003) triggered by concerns over effects of these treatments on non-target organisms. These broad-spectrum biocides act through a variety of toxicity effects resulting from contact, leaching into the water column (an unintended effect) and ingestion. There is a need for more precisely targeted preservatives. Field trial findings alone generate cumulative information about activities of the range of borers at a particular site over a specific period of years. To understand how effective a wood protection method is against specific borer types, single-species lab tests are required. These also have the benefit of yielding results much more rapidly than field tests, enabling the optimisation of treatment protocols and of loadings of active ingredients.

Laboratory tests with marine borers have not reached the precision of standard test methods with beetles and termites. This is partly because of the limited and intermittent demand for testing and partly because of practical difficulties with the borers. Laboratory testing methods with marine borers focus on the types and species of borers that fulfil a number of criteria:

(1) Economically significant as a pest in the region to which the test refers.
(2) Easy to rear in the lab.
(3) Breed under lab conditions.
(4) Breed all year-round.
(5) Robust under experimental conditions.
(6) A body of tolerance data is available to allow optimisation of experimental conditions.
(7) Measures relevant to assessing intensity of attack are available.

Whilst *Martesia* and *Sphaeroma* are locally important, no lab test protocols for them have been described. Testing with *Martesia* would require rearing of phytoplankton (single-celled algae) for food or provision of directly pumped water from the sea. The phytoplankton content of seawater varies markedly between seasons, and spring or summer phytoplankton levels are needed to support breeding. Any test protocols would have to consider whether species-specific measures (criterion 7) would need to be developed. Similar comments apply to *Sphaeroma*, which is also prone to poorly understood microbial growth within their tunnels that make reliable rearing a challenge. To date, the inability to meet the criteria has meant that assays of durability to attack by *Martesia* and *Sphaeroma* have relied on field testing at sites with known activity of these two genera. With criterion 1 in mind, testing should focus on limnoriids and teredinids, with species within the families selected according to the criteria. Selection of species and of culturing conditions is guided by experience with keeping the species in the lab (criteria 2, 5 and 7), information about the life history characteristics (criteria 3 and 4) and about optimum conditions for growth and feeding (criterion 6). Laboratory observations with borer cultures give information regarding the measurement of experimental end points and of rate of damage. Lab data will

guide the optimisation of conditions of water temperature, salinity, other water quality variables such as inorganic nitrogen levels and illumination.

Requirements for an effective lab protocol not only are in many ways similar to those for testing with terrestrial wood-boring invertebrates or fungi but also reflect the marine nature of the organisms with which the tests are being conducted. Key requirements are

(1) excellent water quality,
(2) representative and healthy experimental animals,
(3) tightly controlled and optimum environmental variables,
(4) avoidance of buildup of leachate from wood or treatment,
(5) a closely defined level of borer challenge to the test material,
(6) a measurable level of challenge from borers to the test material,
(7) statistically analyzable measures of the damage to wood,
(8) high survival rates of control organisms.

7.2.3.3 Testing with limnoriids

The northern European *L. lignorum* was the first limnoriid to be described (in 1799) and was used for some of the early developments with lab testing protocols (White, 1929), but the distribution and diversity of economically significant limnoriids is only now starting to be fully appreciated (Cookson, 1991; Borges *et al.*, 2014). More recently, satisfying criterion 1, testing has focused on the widely distributed *L. quadripunctata*, a species whose original distribution is not known and that is suspected of being distributed by wooden sailing vessels to a variety of warm-temperate waters (e.g. California, Chile, South Africa, Australia, New Zealand and northwestern Europe; CABI, 2011) and *L. tripunctata*, which is of particular interest in view of its ability to tolerate the broad-spectrum biocidal effects of creosote, which was known to be effective against other limnoriid species (Zachary *et al.*, 1983). Care needs to be taken to determine the species of test animals as the three limnoriids mentioned above have overlapping ranges, and the anatomical differences between them are quite subtle. They can be distinguished by features on the final body segment, the pleotelson, which forms a discoidal end to the cylindrical body of the animal. These features are used in the keys of Menzies and Cookson (Menzies, 1957; Cookson, 1991).

All species have the same feeding and digestion mechanism. They have a spheroidal head packed with muscles attached to mouth parts that slice and grind the wood through which they tunnel. The resulting minute fragments pass into the stomach where they are packed into a tight columnar mass that passes through the hind gut which extends most of the length of the animal (Cragg *et al.*, 2015). The large digestive gland (hepatopancreas) secretes a range of enzymes suspected of, or in some cases demonstrated to be, active in the degradation of the sugar polymers, particularly cellulose, in lignocellulose. No gut-resident micro-organisms have been reported from limnoriids, so the digestion process is achieved by these endogenous enzymes, one of which has been shown to have a reaction tunnel that forms a precise fit to a cellulose chain (King *et al.*, 2010; Kern *et al.*, 2013). Passage through the gut by the wood particles takes approximately one day (Delgery *et al.*, 2006).

Feeding rate can be measured most readily by counting the faecal pellets produced, as the wood intake per individual animal is too small to measure even with high-precision lab balances (Borges *et al.*, 2009). Fortunately, adult limnoriids produce faecal pellets that are of a reasonably standard size range, so that replication can be made at the level of the individual organism, allowing robust and sensitive statistical methods to be applied to compare faecal pellet production on different experimental materials.

Conditions of lighting do not seem to affect feeding, whilst the temperature optimum for feeding and survival lies within the range normally achieved in an air-conditioned laboratory. Both aspects of experimental conditions are of course convenient for the experimenter. Nonetheless, using a temperature-controlled growth room or incubator with a defined light regime is desirable. Salinity is important and this measure of the saltiness of seawater may increase markedly due to evaporation, particularly if the seawater in cultures is aerated or if the surface area to volume ratio in experimental containers is high. Salinity can be maintained at optimum levels by frequent water changes or addition of deionised water to the culture tanks. Limnoriids are not tolerant of estuarine conditions and thrive at salinities close to that of oceanic water – approximately 35 PSU (practical salinity units; older literature calls these units parts per thousand).

Although limnoriids are likely to retain as much nitrogen as possible, under stagnant water conditions, inorganic nitrogen levels in the water in the form of ammonium, nitrite or nitrate could rise to harmful levels. Nitrogen levels can be regulated by replacing the water in which animals are kept at regular intervals or by passing culture water through a biological filter. Experience shows that replacing water in which animals are kept during laboratory testing should be done twice or even three times a week to keep feeding rates high in control conditions (Borges *et al.*, 2009). This is also desirable to avoid variations between control and experimental timber samples being due to unnaturally high levels of leachate from the experimental timbers (Borges *et al.*, 2008). In this respect, it is noteworthy that sapwood of greenheart (*Chlorocardium rodiei*) is more readily consumed by limnoriids than heartwood (Kühne, 1968).

Laboratory testing procedures with *Limnoria* were pioneered in the BAM laboratory in Berlin. Contact insecticides such as dichlorodiphenyltrichloroethane (*DDT*), lindane, aldrin dieldrin and chlordane impregnated into wood caused mortality within 2 days of contact, whilst 3-month long tests of mortality were conducted with timber treated with a range of combinations of copper chromium, arsenic and fluorine salts (Becker, 1955). A more detailed methodology was described for subsequent tests (Kühne and Becker, 1970) with the important addition of a 4-week leaching period in seawater before *Pinus sylvestris* sapwood blocks measuring 25 mm × 10 mm × 5 mm treated with various copper-containing formulations (with chromium, arsenic, boron and fluorine) exposed to *L. tripunctata* (Kühne and Becker, 1970). Ten individuals of *L. tripunctata* were placed with a test block in a Petri dish containing seawater that was replaced regularly. Mortality reached 90% (the selected end point for this test) after periods of 55 days or more depending on treatment salts and their concentration in the wood. Survivorship and weight loss due to feeding by ten individuals of *L. tripunctata*, *L. quadripunctata* or *L. lignorum* was measured with the same sized blocks over 90 days. Differences between the species were indicated by the findings, but replication levels precluded definitive statistical analysis.

Similar small blocks were used in comparison with proved CCA formulations with the broad-spectrum fungicide chlorothalonil, combined with the insecticide chlorpyrifos (Cookson and Woods, 1995). This study used a well-defined pretesting leaching protocol, replicate tanks and replicate blocks. It added a comparison with a warm-temperate (*L. tripunctata*) and a tropical (*L. insulae*) limnoriid. Attack was measured by a rating system on an arbitrary scale. Contact biocides can be evaluated using a surface dosing protocol developed for insects (Rutherford *et al.*, 1979).

Hardness of wood has been shown by the use of microindentation to mimic the scale at which limnoriid mandibles operate to be a factor in resistance to borer feeding operation, despite saturated wood being softer (Cragg *et al.*, 2007). When testing natural durability of dense timbers, it is recommended to use a non-durable untreated timber with a hardness similar to that of the timbers under test. European beech (*Fagus sylvatica*) may be more suitable than Scots pine (*P. sylvestris*) if denser timbers are being evaluated. Testing with non-biocidal treatments generally termed wood modifications have revealed that such modifications can decrease feeding rates of limnoriids significantly (Klüppel *et al.*, 2015; Slevin *et al.*, 2015), with increased hardness probably being a factor in this decrease (and in potential performance).

Possible confounding factors and factors that complicate the interpretation of experiments on limnoriid feeding include

(1) timber hardness,
(2) toxicity or antifeedant effects of extractive chemicals ingested,
(3) gut toxicity of treatment compounds retained in the wood,
(4) external toxicity by contact biocide,
(5) toxicity of leachate from the wood or wood treatment,
(6) reduced digestibility of the wood,
(7) variation in level of challenge from the borers.

Experimental design should take account of these factors. With regard to factor 5, preleaching before testing is important as leachable compounds can accumulate in the test water at concentrations far in excess of those in water surrounding wooden structures. Thus, leachates of heartwood extractives or preservatives may give an unrealistic impression of the durability of a timber with water-soluble extractives (Borges *et al.*, 2008; Borges *et al.*, 2009). The commonly used feeder block with a colony of borers introduces confounding factor 7 into the design, but this can be avoided in experiments in which feeding of individual animals is monitored. However, feeding rates of moulting individuals should be disregarded as feeding rate dips markedly at the onset of moulting (Delgery *et al.*, 2006).

7.2.3.4 Laboratory testing with teredinids

Whereas limnoriids can spend all or almost all of their life within their tunnels and can disperse to other pieces of wood as swimming adults, the wood-boring bivalves have minute larvae that undergo planktonic dispersal before seeking wood, settling and metamorphosing into sessile adults that are prisoners in their own burrows. Testing with teredinids has to take account of this life cycle. The scientist whose work inspires all wood-borer investigators, Ruth Turner, identified the settlement stage as the weak

link in the cycle and thus the stage deserving close attention in the search for wood protection methods. It should also be borne in mind that teredinids are dependent on bacterial symbionts that inhabit a portion of their gills, fix dissolved nitrogen into organic compounds and contribute to the digestive process. Disrupting the symbiosis between bacteria and host would probably also be an effective antiborer measure.

For successful laboratory testing with teredinids, adults must spawn, and fertilisation must take place either in the water or within the mantle cavity of an adult, with embryological development leading to the larval, veliger stage. Some teredinids brood their larvae on modified portions of their gills. Larvae are released either part way through the veliger stage (as in *Teredo navalis*) or at the settling, pediveliger stage (as in *Lyrodus pedicellatus* and *Teredo bartschi*). Larvae eventually settle then metamorphose and start feeding on at least the control (untreated) wood blocks. Completing the full life cycle is technically more demanding with teredinids than with limnoriids, as larval culture techniques are required and rearing of larval and adult food in the form of microalgae may be necessary. Consequently, fewer lab tests have been developed for these organisms. Successful rearing of *Bankia setacea*, a species with larval development entirely in the water column, has been achieved by providing algal food (Townsley *et al.*, 1966). *L. pedicellatus*, on the other hand, can complete its life cycle without the need for algal food either for adults or for the larvae that are brooded to the pediveliger stage (Pechenik *et al.*, 1979). Its ability to breed at a small adult size is another convenient characteristic for a lab test species. It can be grown in brood stock panels from which larvae are released that can then settle on experimental blocks. It has been used in lab tests with results reported in the form of an arbitrary scale that required a 12-month exposure period for developing evidence of attack and limited the scope for sensitive statistical analysis (Cookson and Woods, 1995). Another test was developed in which larvae were dispensed into a chamber with an array of replicate test and control blocks. Evidence of attempts to settle was counted, and then, blocks were examined at monthly intervals to determine whether postmetamorphosis growth started and continued (Slevin *et al.*, 2015). Clear differences were evident by the end of the first month of observation. The test panels were modified wood rather than biocide treated. Though attempts at settlement were as numerous on the treated as on the control blocks, postmetamorphosis growth only occurred in the control blocks.

7.2.3.5 Conclusions regarding laboratory tests

At present, lab tests with marine borers are designed by the lab conducting the test, but it would be desirable to have standardised tests whose design was influenced by the experience summarised above. The criteria for selection of test organisms have already strongly influenced the organisms selected. The limnoriids *L. quadripunctata* or *L. tripunctata* and the teredinid *L. pedicellatus* have proved suitable for tests focused on wood for temperate to warm-temperate marine use. Meaningful results can be gained within a month of experimentation starting, allowing fine tuning of active ingredient loadings and of treatment process variables after repeated assays. The tests using individual limnoriids allow sufficient biological replication for statistical analysis to determine optima in treatment variables. Tests with feeder blocks

with a colony of limnoriids do not have a well-defined or replicate-able level of borer challenge. To date, studies with teredinids have relied on feeder blocks with this drawback, but with a known number of larvae dispensed onto small experimental blocks, a more quantitative borer challenge would be obtained. These lab tests detect differences between experimental treatments relative to the level of attack on control blocks, but cannot be used to predict service life. However, by selecting for marine trials, only the treatments that cause the greatest mortality or reduction in feeding, much time and cost can be saved.

7.2.4 Moisture dynamics

I. de Windt, W. Willems†*
*Laboratory of Wood Technology – Woodlab, Gent, Belgium
†Firmolin, Deurne, The Netherlands

Moisture is an inevitable part of wood in service. The surrounding air is a source of water that can be adsorbed by wood, and there may be hydraulic contact with sources of liquid water in adjacent materials, soil or rain. Notably in exterior applications, the moisture content (MC) of wood is subject to considerable fluctuations, both in rate and magnitude, imposed by weather changes. Being a building material, wood needs to be able to withstand the dimensional changes and the mechanical stress behaviour associated with these moisture changes, with minimal deformation and check development. Moreover, in a MC range that is reached during the uptake of liquid water by dry wood and during drying of wet wood, wood is susceptible to biological decay, which should remain within acceptable limits. Clearly, the moisture behaviour of wood is one of the key issues in the characterisation of service performance. In this respect, the total amount and type of moisture states in wood, absorption rate of water liquid and water vapour uptake are all relevant.

7.2.4.1 Moisture storage in wood

Dry wood is a porous solid, consisting of dense wood substance and interspersed pores. The volume of wood substance in a specimen is measured by pycnometry as the volume of space that cannot be occupied by a pore-filling medium (Walker, 2006). The measured pore volume is then dependent on the molecular size of the probe medium, with helium being the finest probe. The typical true density of wood substance is 1500 kg/m^3, as determined by Helium (He) pycnometry (Skaar, 1988). The massless part of the bulk volume of porous wood can then be assigned to pores.

The volume distribution of pore sizes in wood can be measured – among other methods – by mercury intrusion porosimetry (*MIP*; Zauer *et al.*, 2014). In MIP, increasingly smaller pores are filled with mercury, requiring a higher hydrostatic pressure of the mercury fluid, to overcome the repulsive capillary forces. Each increase of hydrostatic pressure corresponds to the filling of a well-defined range of pore radii.

When water is used as the pore-filling medium, the uptake is spontaneous, since the capillary forces are attractive (capillary suction) due to the presence of polar chemical groups at the wood pore surfaces (Wang *et al.*, 2015). At full saturation of dry wood with water, the absorbed volume of bulk water exceeds the total pore volume of dry wood, as determined by He pycnometry or MIP. The excess is explained by the uptake of water inside the dense wood substance (matrix), as evidenced by the elastic volume swelling of the wood matrix (Skaar, 1988). A non-polar media (e.g. helium, air and hexane) cannot cause the wood matrix to swell, whereas polar media (e.g. water, dimethyl sulfoxide, ethanol and acetic acid) can.

7.2.4.2 *Characteristic* MCs

Tiemann (1906) noted that the uptake of moisture in wood takes place in two distinct regimes with a transition around a fibre saturation point (*FSP*). Below the FSP, all moisture is considered to exclusively take place within the wood matrix, whereas above FSP moisture is exclusively accommodated in empty pores (capillaries). Theoretically, there is no mechanism that prevents the capillary condensation of moisture below FSP, but Engelund *et al.* (2010b) found that its quantitative contribution to the total MC is negligible when MC < FSP. Only after the matrix has approached a limiting MC and maximally swollen state, which occurs in a nearly fully saturated humid environment, the remaining larger-sized pores start to take up significant amounts of moisture. The transition from below to above FSP and vice versa is most relevant in the study of exterior service applications, where wood is exposed to alternating periods of rain and drying conditions.

The FSP is often determined indirectly, as identified by the point of a MC trend change occurring in some physical parameter of choice (e.g. dimension swelling, electrical conductivity, gas permeability, modulus of elasticity and proton magnetic resonance relaxation time). Confusingly, measured FSP values range from 25% to as much as 60% obtained on one piece of wood, depending on the experimental method (Skaar, 1988; Zelinka *et al.*, 2016) and the preparation details of the specimen (Hoffmeyer *et al.*, 2011).

A better (than FSP) defined moisture characteristic is the saturated MC by soaking wood into water in a vacuum container, whereby the specimens are allowed to deaerate before the imbibition with water, to prevent trapping air in the porous network. The uptake of bulk water by the wood matrix and by the capillary porous network is a spontaneous process, dissipating heat of adsorption. Immersion calorimetry is used to collect and quantify this heat during saturated wetting of oven-dry wood (Skaar, 1988), expressed as the specific heat of immersion (dissipated heat energy per mass unit of dry wood). This quantity is thought to be directly proportional to the total number of bound water molecules in wood (Skaar, 1988; Willems, 2016).

7.2.4.3 *Dynamic mechanical effects in the wood matrix*

The limiting MC of the wood matrix is determined by several factors. The driving force for water absorption of the wood matrix is the physical interaction strength between the wood components and water and, in particular, the hydrogen-bonding strength

(Chirkova *et al.*, 2013; Mantanis *et al.*, 1994). In wood, the abundance of accessible hydroxyl groups is the most important metric for the moisture sorption potential of the wood matrix (van Krevelen and Hoftijzer, 1976). Each hydroxyl group has a sorption capacity for 1–1.2 water molecules (Berthold *et al.*, 1996; Willems, 2014a). However, the driving force for adsorption is counteracted by the elastic forces that are generated in the swelling wood matrix as moisture is being absorbed (Flory and Rehner, 1943; Papadopoulos and Hill, 2003). The wood matrix becomes water-saturated when the driving force has been cancelled by the accumulated elastic counterforces, regardless of the remaining concentration of unoccupied accessible hydroxyl groups (elastic limit). Alternatively, water saturation is reached when all accessible hydroxyl groups are occupied before the elastic forces have accumulated enough strength to stop the ingress of water (sorption site limit).

The dynamical behaviour of wood adds complexity to the above view; for example, (a) the hydroxyl group accessibility may decrease by drying or temperature increase (Suchy *et al.*, 2010), (b) the modulus of elasticity of the wood matrix changes with MC (Back and Salmén, 1982) and in slow response to moisture changes (Hæggström *et al.*, 2006; Jiang *et al.*, 2012), (c) mechanical stresses imposed on wood by moisture gradients interact with the local elastic forces governing the limiting moisture uptake (Skaar, 1988) and (d) vacuum soaking in water may lead to a realignment of wood polymers (Altgen and Militz, 2016). In summary, one must be very cautious of dynamical structural effects in wood when characterising the moisture behaviour.

7.2.4.4 Equilibrium moisture content

Wood will eventually attain equilibrium moisture content (*EMC*) in unsaturated water vapour at a fixed relative humidity (*RH*), which is defined as the fraction or percentage of saturation of the surrounding water vapour (Skaar, 1988). A constant RH environment can simply be obtained in a closed container above saturated salt solutions (Wexler and Hasegawa, 1954), where the desired RH-level between 0% and 100% can be achieved by the appropriate choice of salt. Alternatively, a climatic chamber or automated dynamic vapour sorption (*DVS*) equipment (Engelund *et al.*, 2010a) with continuous electronic (RH, T) control can be used.

However, it is difficult to control humidity levels accurately near saturated humidity conditions (RH >98%) in experiments to study the matrix-capillary moisture transition around the FSP in detail. The pressure plate method (Fredriksson and Johansson, 2016) employs the measurement of EMC in saturated water vapour, whilst the sample is subjected to an elevated hydrostatic pressure. This hydrostatic pressure is related to a well-defined humidity equivalent at atmospheric pressure (Willems, 2014b), allowing more accurate – but extremely slow – EMC measurements near FSP at high RH.

The EMC is measured as the MC after a 'sufficient' conditioning time at set RH and temperature values, which may be experimentally checked by having obtained a constant sample mass. However, the MC may continue to change over extended periods of time at constant RH and temperature, leading to an impractically long duration of the experiment. It is up to the experimenter to choose the appropriate observation time, depending on his/her research objectives. A prerequisite for meaningful

EMC readings is that there are no residual MC gradients in the sample, giving preference to the use of thin samples. One must be aware of progressively slower transient MC kinetics at increasing RH (Christensen and Kelsey, 1959; Kelly and Hart, 1970; Engelund *et al.*, 2013).

Sorption isotherms are characteristic graphs relating the EMC to various relative humidity (RH) at a fixed temperature (T). In case of wood, sorption isotherms have quite generally a sigmoid appearance, which is concave at low RH and convex at high RH. The exact mechanisms that account for this curve shape are still a subject of scientific study (Engelund *et al.*, 2013). Because of dynamical structural responses to moisture changes in the wood matrix, the EMC versus ascending RH (adsorption) is different from the EMC versus descending RH (desorption). The desorption isotherm is always located above the adsorption isotherm, requiring a lower RH in desorption than in adsorption for establishing one EMC. This phenomenon is called 'sorption hysteresis' (Engelund *et al.*, 2013). The significance of sorption isotherms for the service performance of wood is that less steep adsorption isotherms predict smaller moisture changes with RH fluctuations and hence a better dimensional stability of the wood product.

7.2.4.5 *Measuring* MC

Moisture measurements can be performed directly or indirectly. Direct methods are based on removing all water from the material; indirect methods measure a certain characteristic related to the MC of the material. Wood MC can be measured in several ways. A few frequently used techniques are discussed below.

7.2.4.6 *Gravimetric method (CEN/TS 13183-1)*

The most classical way to obtain moisture concentration profiles is the gravimetric method. The MC is calculated easily by successively weighing the specimens, drying the specimens in an oven by 103 ± 2°C till constant mass and weighing them again.

By convention, the moisture content (MC) of wood is quantified by the mass ratio of wood moisture to moisture-free wood (fraction or percentage) using the following formula:

$$\mathrm{MC} = \frac{m_1 - m_0}{m_0} \tag{7.1}$$

where MC is the moisture content, in percent; m_1 is the mass of the test specimen before drying, in grams and m_0 is the mass of the oven-dry test specimen, in grams.

Moisture-free wood is obtained by oven-drying at 103°C until mass constancy. At full water saturation of a wood specimen, it appears that the bulk volume equivalent of all wood moisture significantly exceeds the total pore volume of oven-dried wood.

Although this is the most direct method for determining the overall MC, it has two major disadvantages. First of all, it is a destructive technique and therefore difficult to use when a profile is aimed for. Secondly, the method is not accurate in its spatial resolution. The MC is the average over the total sample.

7.2.4.7 Electrical resistance (CEN/TS 13183-2)

Due to the high sensitivity of an electrical resistance, R, to moisture, an electrical resistance moisture metre can measure the local MC with high accuracy. The measurements are based on the linear relationship between $\log R$ (Ω) and MC (%) below FSP.

Two insulated electrodes are inserted into the wood vertical to the grain. By measuring MC at different depths, an estimation of the moisture profile can be generated.

Although a quick and relatively accurate technique for estimating a more local MC, resistive methods are not suitable for registering local moisture variations.

7.2.4.8 X-ray tomography (X-CT)

X-ray computed tomography (X-CT), which is basically taking several projection images or radiographies at different angles, was first applied for medical purposes. Nowadays, X-CT scanning is a non-destructive test method that makes it possible to study the internal structure of, the density of and the moisture distribution in bio-based materials over time. MC measurement using a *CT* scanner is an indirect measurement method, as the CT number is coupled to the density of the material and water and not to the MC itself.

An X-ray radiography is based on the principle of transmission. From an X-ray source, the beam passes through a specimen where the photons will interact with the electron shells of the atoms. The transmitted radiation is detected as a 'shadow image' in the format of a two-dimensional matrix by the radiation detector (Mannes and Lehmann, 2007; Lehmann and Mannes, 2012). A schematic overview is given in Fig. 7.9.

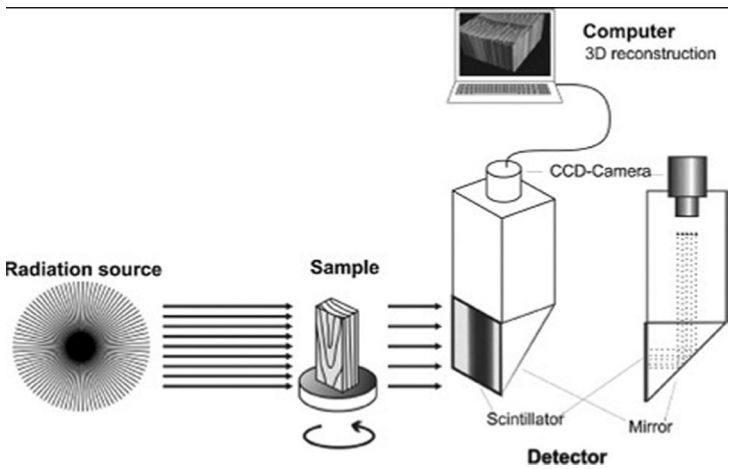


Fig. 7.9 Setup for transmission radiation image: a beam of radiation is sent through the object of investigation and two-dimensional image detector registers the transmitted intensity; when the specimen is rotated around its axis, the technique can be extended towards tomography data acquisition (Mannes, 2009).

The tomography technique uses many of these X-ray projections to slice-by-slice reconstruct the object in three dimensions. For more detailed information on the basic principles of X-CT, the reader is referred to Kak and Slaney (2001).

Within each slice, the transmitted X-ray intensity data are used to calculate the average X-ray linear attenuation coefficient for each volume element (voxel), based on the attenuation law of Beer-Lambert (Herman, 1980). Each individual voxel is assigned an attenuation coefficient, corresponding to the density of the region of interest and depending on the chemical composition of the material. The attenuation coefficient μ also strongly depends on the emitted X-ray energy spectra and thus is normalised against distilled water as an internal standard according to

$$\mu_{\text{rel}} = 1000 \times \left(\mu_{\text{material}} - \mu_{\text{water}} \right) \times \mu_{\text{water}}^{-1} \tag{7.2}$$

The density information of the μ_{rel}, also called the CT number, is transferred into grey values for the CT images, which leads to dark colours for areas of low density and brighter colours for areas with increasing density.

Since there is a linear relationship between density and MC, the intensity in the image is proportional to the amount of water. A darker colour indicates low density and white areas indicate high density and, because of this, increased water content (Sandberg and Salin, 2012).

Moisture distribution can be calculated by subtracting the data matrices of the wetted and successively oven-dried wood scanned from each other. However, when the moisture distribution in the specimen is of interest, the images must be geometrically transformed because wood shrinks during drying, which impedes comparison with the images. Therefore, the density of wood substance and hence the CT number have to be corrected. Digital image correlation (*DIC*) is a promising technique for measuring local displacements and strains in images (Fig. 7.10) (Watanabe *et al.*, 2012). Still further research on the topic is needed as the method is currently not applicable in every test setup.

7.2.4.9 Neutron imaging

Neutron imaging (*NI*) is a non-destructive, indirect laboratory method based on the same basic principles as X-ray radiography, namely, transmission measurement. When a beam of low-energy neutrons passes through a material, the neutrons, unlike X-rays, will interact with the nuclei of this material. Depending on the constitution and inner structure of the material, the neutron beam is attenuated and subsequently registered by a detector system as a two-dimensional data set of grey level values in individual pixels (Mannes and Lehmann, 2007). The attenuation of the neutron beam is determined by the cross-section for scattering and absorption of the nuclei present in the sample. Because of the relatively large scattering cross-section of hydrogen, neutron radiography has been shown to be an accurate and reliable method for determining the MC in wood (Pel *et al.*, 1993; Sedighi-Gilani *et al.*, 2012). The technique allows visualisation of the spatial distribution of water and high-resolution quantification of water content in porous media. It provides higher resolution for the determination of the MC than *MRI* and X-ray radiography (Mannes *et al.*, 2009).

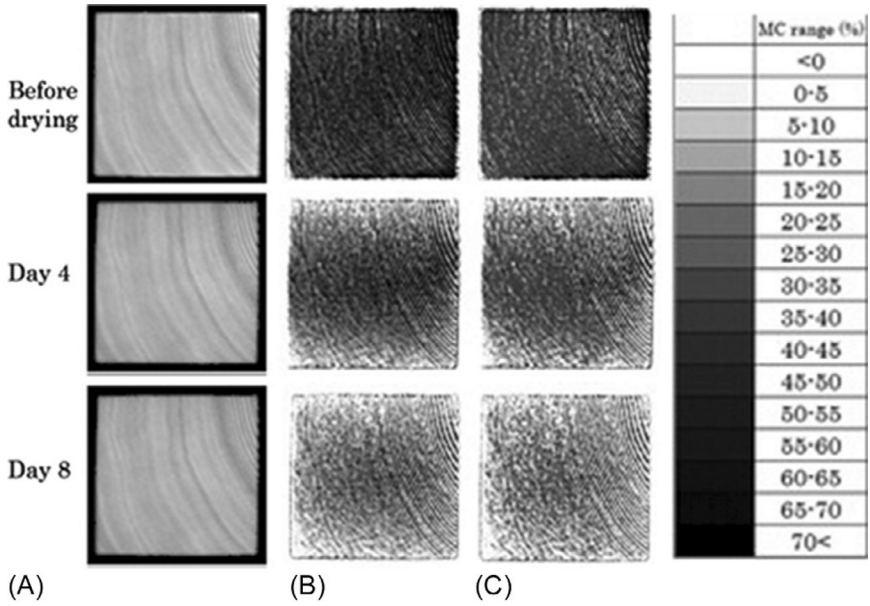


Fig. 7.10 (A) CT images of a cross-section from the centre of a specimen ($l \times w \times h$: 900 mm × 115 mm × 115 mm) amabilis fir (*Abies amabilis*) during the drying process. A *darker colour* indicates low density and a *lighter colour* indicates high density. (B) MC distributions calculated by DIC analysis and (C) iterative approximation during the drying process. A *darker colour* indicates a higher MC value. The image is composed of 450 × 450 pixels with a spatial resolution of about 0.25 mm (Watanabe *et al.*, 2012).

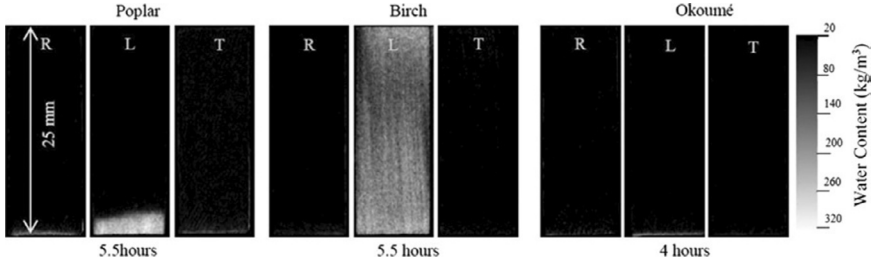


Fig. 7.11 Water distribution in three solid wood species along three different directions after several hours of water uptake (*R*, radial; *L*, longitudinal; *T*, tangential) (Li *et al.*, 2014).

The MC at time *t* can be determined by measuring the variation in beam intensity ascribed to water ingress in respect to the initial situation (Fig. 7.11) (Sedighi-Gilani *et al.*, 2012; Li *et al.*, 2014). Water content is equivalent to the water thickness change, as it is considered that wood swells in the direction parallel to the neutron beam. Consequently, the water content in the specimen (kg/m^3) at time *t* is given by the following formula:

$$W_t = -\left[\frac{\rho_h}{\left(Z_s * \sum h\right)}\right] * \ln\left[\frac{I_t}{I_{\text{initial}}}\right] \tag{7.3}$$

W_t is the water content at time t, ρ_h the density of water (kg/m^3), Z_s the thickness of the specimen along the neutron beam, $\sum h$ the attenuation coefficient per unit of water, I_t the intensity of the transmitted beam at time t and I_{initial} is the intensity of the transmitted beam before absorption.

7.2.4.10 Nuclear magnetic resonance imaging

Since the success of nuclear magnetic resonance imaging (*NMRI*) in medical diagnostics, this technique has been extensively explored in wood science. Due to its noninvasive nature, high spatial resolution and sensitivity to the dynamical state of water, NMRI is an exquisite tool for monitoring moisture distribution in wood (Dvinskikh *et al.*, 2011). Unlike X-CT or NI, NMRI can make a distinction between chemically and physically bound water (Pel *et al.*, 1993).

To image an object, nuclei with an odd number of protons and/or neutrons, for example, ^{1}H and ^{13}C, are exposed to an external magnetic field B_0. The nuclei align their magnetic moment vectors in the direction of B_0. Then, a radiofrequency (*RF*) magnetic pulse B_0 is generated by an RF coil, and as a result, the magnetisation vectors rotate proportional to the amplitude and duration of the RF wave (resonance). Once the excitation RF wave stops, the nuclei will precess to their initial equilibrium whilst releasing the absorbed energy (relaxation). This precession can be measured by the RF receiver, which is the same as the coil generating the RF pulses. The energy is released through the phenomena of longitudinal or spin-lattice relaxation (T1) and transversal or spin-spin relaxation (T2). These relaxation times reflect the environment of the studied nucleus at a molecular level and thus reveal the biochemical information of the studied object (Chang *et al.*, 1989; Wang and Chang, 1986). T1 and T2 relaxations for water in wood are very different from that of pure water (Passarini *et al.*, 2015).

To spatially encode the emitted signal, a magnetic field gradient is imposed on the main magnetic field. Such a gradient causes nuclei at different positions to have different frequencies. By analysing the transverse decay curve of ^{1}H in wood, three main components could be described: solid wood with fast T2 (10′s µs–1′s ms), the cell-water signal with medium T2 (1–10′s ms) and liquid water in cell lumina with slow T2 (10–100′s ms) (Araujo *et al.*, 1993; Menon *et al.*, 1987). The intensity of the signal will be lower as the MC, and thus ^{1}H decreases (Fig. 7.12).

7.2.4.11 Moisture dynamics

The MC of wood and wood-based materials is one of the deciding factors whether wood rot fungi will occur and grow (Brischke *et al.*, 2006; Viitanen *et al.*, 2010). It is commonly agreed that the moisture conditions for decay fungi become favourable when the MC of the materials ranges from 22% to 30% depending on the wood species. Therefore, the wetting ability and the ease of drying afterwards are of primary interest to assess the risk of decay.

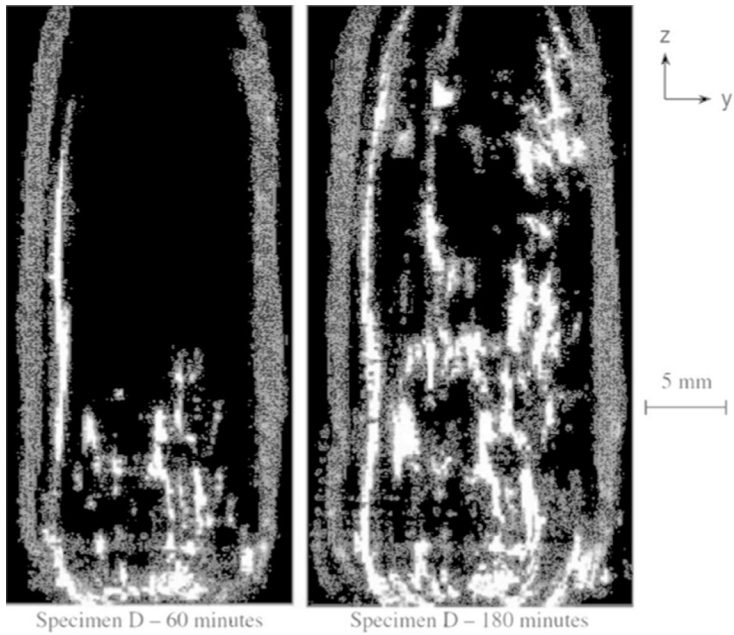


Fig. 7.12 NMR image of an OSN specimen sealed at edges and soaked in water for 60 min *(left)* and 180 min *(right)* (van Houts *et al.*, 2004).

In order to monitor the MC and consequently the water entrapment in several wood-based materials, several techniques, for instance, magnetic resonance imaging, X-ray scanning and NI, can be applied (Van Houts *et al.*, 2004; Mannes and Lehman, 2007; Li *et al.*, 2014). Although very well suited for in-depth research, these methods are time-consuming or expensive and thus difficult to be used as a routine assessment technique.

An efficient laboratory-scale method is developed to calculate and predict the water entrapment in wood-based materials. The protocol will soon become a European standard test method (prEN 16818, CEN, 2015b).

As the moisture behaviour of wood and wood-based materials is affected by both surface and end-grain phenomena, the test methodology to assess the moisture dynamics considers 'floating testing' and complementary 'submersion testing'.

7.2.4.12 Floating test

The floating test method is based on a sorption/desorption method for solid wood as proposed by Rapp *et al.* (2000) and is to some extent also related to EN 927-5 (CEN, 2006b), which is developed for testing liquid water permeability of a coating for exterior wood.

To reveal how fast water enters the material and how fast it dries out, edge-sealed specimens were left floating freely on water. At regular intervals, the water uptake was

determined gravimetrically. The absorption phase was followed by a desorption phase during which the specimens were left drying to recondition until constant mass was reached.

7.2.4.13 Submersion test

As timber and wood-based materials are prone to axial water uptake, a submersion test is added to the test setup. Specimens with open end-grain cross-sections are soaked in water. As for the floating test, the specimens are weighed at regular intervals to register their mass gain. Mass loss is measured by weighing the specimens during drying at regular intervals.

From the abovementioned tests, two important characteristics can be derived: the absorption coefficient and the residue. The absorption coefficient as a measure for wetting ability is derived from the increase in weight of the test specimen during the absorption phase versus the square root of the time (Mukhopadhyaya *et al.*, 2002). The residue represents the moisture left in the test specimen after desorption as a percentage of the absorbed moisture and indicates the risk of water accumulation.

Both tests generate curves, of which the parameters show the potential to discriminate between wood species along their moisture behaviour (Van Acker *et al.*, 2014). A brief description of the approach to assess the materials performance through the sorption/desorption test is given below.

7.2.4.14 Discrimination of wood species based on moisture dynamics

The absorption curves fitted for both the floating test and the submersion test are based on the formula

$$f(x) = ax^b \tag{7.4}$$

When the *b*-value is close to 0.5, one can expect the *a*-value to be a parameter related to the absorption coefficient. Deviating values of *b* can point at special absorption phenomena like impact of capillary uptake.

The desorption curves are somewhat more complex and were based on the formula

$$f(x) = a + be^{(-x/c)} \tag{7.5}$$

The *a*-value is the asymptotic value after drying and corresponds to the residue. The *b*-value equals the amount of moisture that is released. Hence, the sum of the parameters *a* and *b* should be similar to the total absorption. The parameter *c* is corresponding with the drying rate of the material. Low *c*-values correspond with fast drying. High values of these three parameters correspond to high risk of water accumulation.

Consequently, controlling the wood MC is of primary interest to assess the risk of decay although the presence of active ingredients both from natural origin as induced by wood preservation can be used to supplement or overrule the impact of moisture dynamics (Van Acker *et al.*, 2015).

7.3 Field methods

7.3.1 Decay fungi, staining fungi, mould and bacteria

L. Meyer-Veltrup, L.R. Gobakken†*
*Leibniz University Hannover, Hannover, Germany
†Norwegian Institute of Bioeconomy Research (NIBIO), Oslo, Norway

The test methods described in this chapter are primarily used for testing wood or wood-based materials. Furthermore, when testing natural durable or modified materials, one has to keep in mind that most test protocols, especially the standardised ones, were developed to determine the effectiveness of wood preservatives against decay fungi and other degrading micro-organisms. Therefore, they might need to be adapted to the special characteristics of the respective bio-based material undergoing testing. In areas where termites occur, the in-ground tests especially have to be seen as a combination of tests against both decay fungi and termites. To avoid attack by termites, special protective measures would be needed.

7.3.1.1 Decay fungi

In ground exposure – non-standard methods

Testing wood in ground is almost exclusively conducted according to the so-called graveyard test (EN 252, CEN, 2014b and AWPA E7, AWPA, 2013a; Fig. 7.13). In this test, stakes of 25 mm × 50 mm × 500 mm are buried into the ground by half of their length. Once a year, all specimens are rated using a prick test where a pointed knife is pricked into the specimens and backed out again. The fracture characteristics of the splinters and the depth and distribution are assessed visually and evaluated according to a rating scheme given in the standard.

In ground exposure – non-standard methods

Non-standard in-ground test methods differ only in specimen size compared with the standard graveyard tests. Examples are the so-called mini-stake test conducted

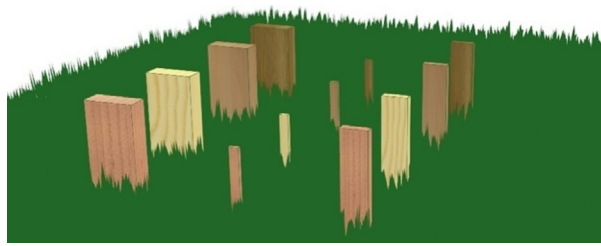


Fig. 7.13 In-ground test methods. From *left* to *right*. Double size stake test, mini-stake test and standard graveyard test according to EN 252 (CEN, 2014b) and AWPA E7 (AWPA, 2013a).

by Westin *et al.* (2004) and Brischke *et al.* (2014) and the double-size-stake test conducted by Meyer *et al.* (2013, Fig. 7.13).

Above ground exposure – non-standard methods

Among all test methods that are primarily used for testing wood or wood-based materials in above-ground situations, only a few are standardised. The two tests that are conducted most frequently are the L-joint (EN 330, CEN, 2014c and AWPA E9, AWPA, 2013b) (Fig. 7.14A) and the Lap-joint (CEN/TS 12037, CEN, 2003 and AWPA E16, AWPA, 2013c) (Fig. 7.14B) tests. Both methods are composed of two members creating a joint or water trap, respectively. With the L-joint test, consisting of a tenon and a mortise member, a coating is applied that is intentionally broken to simulate a poorly constructed and maintained component, that is, window joinery. For both tests, the end grain needs to be protected with a flexible end sealant. Other standardised test methods are the ground proximity test (AWPA E18, AWPA, 2013d; Fig. 7.14C), the exposed decking test (AWPA E25, AWPA, 2013e; Fig. 7.14D), the accelerated lap-joint test (AWPA E27, AWPA, 2013f; Fig. 7.14E) and the Australian flat panel test (AWPC, 2015; Fig. 7.14F).

Above ground exposure – non-standard methods

The number of non-standardised methods for testing bio-based building materials above ground is remarkably higher compared with the standardised methods. Most of these tests were, again, developed to determine the effectiveness of wood preservatives against decay fungi or to compare different wood species or treatments.

A literature study undertaken in 2014 revealed in total 54 different test procedures that were used in various field tests (Meyer *et al.*, 2014). The different tests can be grouped by their design as follows: (1) the number of test components: from single

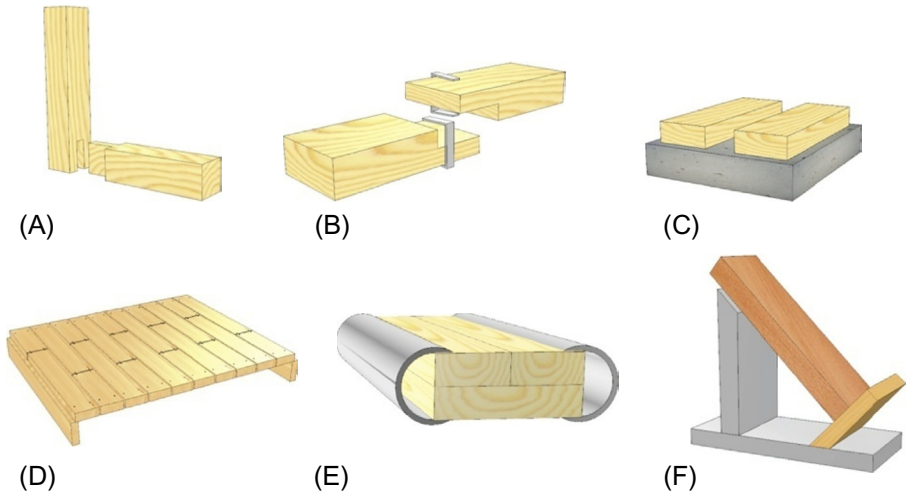


Fig. 7.14 (A) L-joint test setup. (B) Lap-joint test setup (no end-grain sealing was applied, since the specimens are not treated) (C) Ground proximity test, (D) Exposed decking test, (E) Accelerated Lap-Joint test and (F) Australian flat panel test.

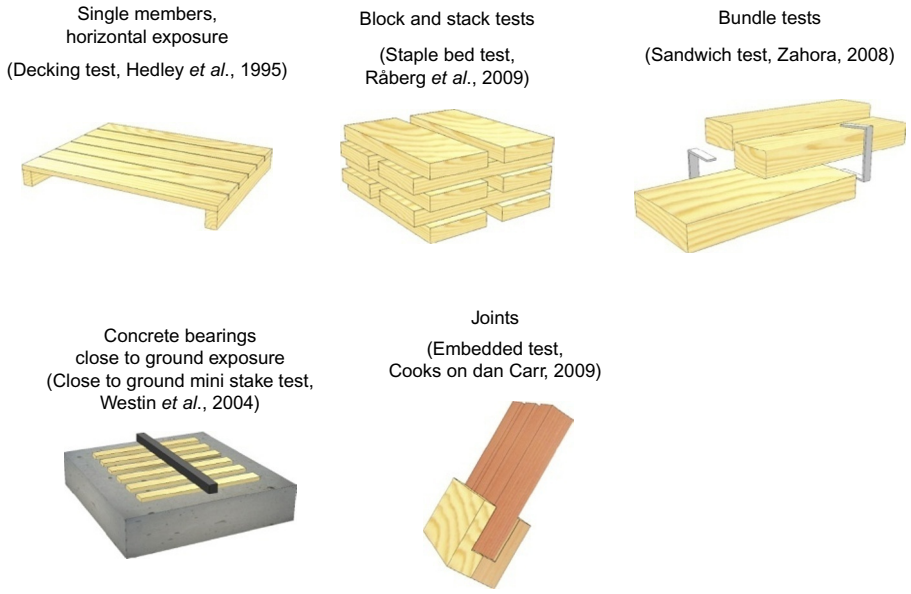


Fig. 7.15 Different above-ground test setups.

member to two or more members creating joints or water traps and (2) the exposure situation – horizontally, vertically, specific angle, far above ground or close to ground. Additionally, it was found that a lot of these tests were again modified by different authors that used acceleration measures like additional water traps or feeder boards.

A few examples for the different design principles and exposure details are given in Fig. 7.15.

Accelerated methods

In-ground tests benefit from short test durations. Whilst tests in ground contact can provide final results after one to 5 years, depending on wood species, treatment or modification (Larsson Brelid *et al.*, 2011), failure in above-ground tests caused by decay can take decades (Wang *et al.*, 2008). However, since the majority of timber products are exposed without ground contact (façades, terrace decking, windows, balconies or carports), above-ground test results ensure a more accurate transferability of results to real-life situations.

To overcome the drawback of the longer test duration, different acceleration measures were added to some above-ground tests, wherefore they must be interpreted as different or actually new test methods (e.g. Vidović, 1981; Van Acker and Stevens, 1997; Zahora *et al.*, 2013). These measures include water trapping, artificial shading, modified bearings, feeder boards or coating.

7.3.1.2 Mould and staining fungi

Fungi causing dark discolouration and disfigurement to stored wood (freshly logged timber and stored logs) and wood/bio-based materials in service are often referred to

as staining fungi, or more specifically, sapstain for stored wood and blue stain in service for wood in service. Mould is most often referred to as superficial fungal growth on wood and other types of bio-based materials. Sapstain, blue stain and mould are normally only considered on wood and bio-based materials tested in above-ground situations.

Standard methods

Wood materials intended for use in building facades and other types of vertical applications above ground are often tested according to EN 927-3 (CEN, 2012b). The standard is originally designed to assess the performance of wood coating systems during outdoor exposure and one of the properties that are assessed is blue stain and mould growth. Specimens with the dimension 20 × 79 × 375 mm are mounted horizontally at an angle of 45 degree in racks exposed against the south (Fig. 7.16). Evaluation of mould growth is made after 12 months according to ISO 4628-1 (ISO, 2016).

For freshly felled timber, CEN/TS 15082:2005 is used to assess the effectiveness of wood preservative products against colonisation by sapstain, mould and other disfiguring micro-organisms. The test should be carried out on sites where targeting organisms are known to colonise untreated susceptible timber species and in periods when the fungal activity is proven to be high. Specimens with the dimension 100–120 × 18–25 × 100 mm (or more) are stacked with spacers making both an open-stacked and closed-stacked storage condition. First grading (assessment) is made after 3 months according to a defined grading system describing the amount of disfiguring micro-organisms.

Non-standard methods

Many of the non-standard tests performed on wood and wood-based materials for assessing their susceptibility to mould and blue-stain fungi are often based on EN 927-3 (CEN, 2012b). The deviations from the standard in these tests are often in sample size,

Fig. 7.16 EN 927-3, Bogesund field site, Sweden.
Courtesy of Lone Ross Gobakken.

Fig. 7.17 *Left* from Rüther (2011), *right* from Gobakken *et al.* (2010). Courtesy of Lone Ross Gobakken.

mounted angle of samples, evaluation intervals and exposure to cardinal direction, and the design of the test setup is made to accommodate the aim of the specific study better. Fig. 7.17 gives two examples of non-standard or modified standard methods.

Assessment of growth of moulds and blue-stain fungi is also performed as an additional variable or property on samples tested in traditional test set-up for decay resistance above ground. When testing decay resistance of wood materials according to tests for above-ground situations summarised in Section 7.2, also the mould and blue-stain performance may be rated at the same time (e.g. Schabacker *et al.*, 2013).

Rating of discolouration

Assessment of mould and blue-stain development are done according to scales defined in standards (e.g. EN 16492 (CEN, 2014e); ISO 4628 (ISO, 2016); EN 15457 (CEN, 2014d); BS 3900-G6 (BS, 1989); EN 152 (CEN, 2011)) or specific scales developed and designed for the purpose (e.g. Viitanen and Ritschkoff, 1991; Johansson *et al.*, 2012; Van Nieuwenhuijzen *et al.*, 2015). In EN 927-3 (CEN, 2012b), the assessment is made according to ISO 4628-1 (ISO, 2016) and EN 16492 (CEN, 2014e) where the intensity, quantity and size of the defects or growth are rated from 0 (=unchanged/none/not visible) to 5 (=very marked/dense pattern/larger than 5 mm). Ratings based on several of these standardised and non-standardised scales give ordinal data, not continuous, since the scale either takes into account shape and pattern or the scale defines other types of ordinal classification. The quality and accuracy of the visual assessment of mould and blue-stain fungi according to a fixed scale is dependent on the subjective skills of the evaluator. Due to this and the wish for continuous assessment data, multisensory techniques and digital image processing have been studied and with very promising results (e.g. Terziev, 1997; Van den Bulcke *et al.*, 2005; Van den Bulcke *et al.*, 2006; Gobakken *et al.*, 2009; Burud *et al.*, 2015).

Bacteria

When testing durability in the field, especially in ground contact, bacteria are always present and appear as primary or secondary colonisers (Schmidt, 2006). Wood-degrading bacteria are divided into three groups: erosion bacteria, tunnelling bacteria and cavitation bacteria. CENT/TS 15083-2 (CEN, 2005d) gives a short overview about the identification of degradation caused by tunnelling bacteria. Although no particular tests for degradation by bacteria exist, the presence and degree of attack are by many evaluators registered when found on samples in various in-ground decay tests to serve as added information of the performance.

7.3.2 Insects

S. Curling
Bangor University, Bangor, United Kingdom

Generally field tests are performed only for termites out of all the insects that attack bio-based materials, as they are a major source of economic damage. Field testing is used to gain information on the durability of materials or the effectiveness of treatments in a real-world situation. They rely on natural sources of termites and the ability of the termites to find the material and can thus take a number of years to complete. In some cases, test assemblies are attached or connected directly to termite colonies, and in others, assemblies are placed in infested areas and 'baited' with untreated wood. Many test methods are modified and optimised for local climatic and termite species reasons, and therefore, the choice of a particular field test site can be critical. When testing commodities or products, it is therefore important to use more than one field site or climatic zone.

In essence, all of the differing test methods involve placing test specimens near, on or in the ground, allowing termites to find the specimens and then assessing the damage caused. The ground proximity test (Preston *et al.*, 1985) is now used by the American standards AWPA E21 (AWPA, 2015a) and E26 (AWPA, 2015b). Hollow concrete blocks are placed onto the ground surface with the test specimens placed on top of the blocks, in between untreated blocks that act as feeder blocks. E21 uses larger blocks with a pine stake driven through the centre of the block and is readily adaptable for non-wood products. The assembly is covered to stop rain ingress. Assessment is by visual rating from 10 (no attack) to 0 (failure).

Japanese standard JIS K 1571 (JIS, 1998) uses a form of this test also known as a flowerpot test. In this method, the specimens are placed onto a concrete or brick block with untreated feeder strips adjacent to them to allow termite access. The assembly is then covered with an upturned ceramic box flowerpot or cover to prevent rain ingress. Once per year, the blocks are assessed and rated according to the scheme shown in Table 7.6; mass loss can also be used if necessary.

Another approach is to use a container packed with both untreated (to attract termites) and treated test samples. In Australian protocols, a 20–30 L cylindrical steel drum is used, which is placed adjacent to a termite colony. PVC piping partially filled with untreated wood connects the colony to the drum (Creffield, 1994, AWPC, 2015). The test usually lasts between 6 and 12 months and is assessed by visual rating of remaining wood and/or by mass loss of the samples at the end of the test (AWPC, 2015). Australian methods utilise a system of trenches filled with susceptible wood material to link test specimens and/or containers to a termite colony (Howick and Creffield, 1983).

Stake tests similar to EN 252 (CEN, 2014b), where a wooden stake is partly driven into the ground vertically, are also used (AWPC, 2015; Ncube *et al.*, 2012; Lenz *et al.*, 2012) although in areas prone to wild fires test specimens can be buried completely in a horizontal position (Lenz *et al.*, 1992; Lenz and Creffield, 1993). In some cases,

Table 7.6 Rating scheme for termite field test, according to JIS K 1571 (JIS, 1998)

Rating	Description
0	Sound
10	Shallow damage on part of the surface
30	Damage reaching the inner part of specimen on part of the block
50	Damage to wide areas of the inner parts of the block
100	Failure

Table. 7.7 Correlation of visual damage rating and weight loss with durability class as defined by EN 350 (CEN, 2016e)

Damage rating	Weight loss (%)	Durability class
0–1	0 to <5	Durable
2–3	5 to <20	Moderately durable
4–5	>20	Susceptible

feeder strips are used to link specimens to make it easier for termites to locate samples (Howick and Creffield, 1983; AWPC, 2015).

These types of tests are generally used to determine fungal decay of wood but when used in areas of termite infestation are also tests of the susceptibility to termites. The method is also applicable to non-wood materials such as plastics (Lenz *et al.*, 2012). Assessment is by rating and weight loss and can be used to determine durability as defined in EN 350 (CEN, 2016e) (Table 7.7).

A larger test assembly used to test timber frames or sills is a simulated house test. Here, timber is used to assemble or make a box-like 'house' with walls and a roof that can be easily inspected for termite damage. This type of test is heavily dependent on the locale and termite species. Larger versions have been used in Japan (Suzuki, 1999) to simulate a full-scale house.

7.3.3 Marine borers

S.M. Cragg
University of Portsmouth, Portsmouth, United Kingdom

The equivalent of terrestrial field tests is marine trials. These involve long-term exposure at sites with high marine borer activity of precisely prepared, treated or naturally durable timber specimens. The value of marine trials is that they assess resistance to borers under conditions that are close to those in service: larger dimension wood samples, natural leaching, exposure to UV if placed intertidally and a combination of borers. The results obtained give a cumulative picture of the way borer attack is affected by recruitment seasonality, success after settlement, active ingredient loss

and effects of microbial colonisation. However, marine trials have a number of drawbacks. They require significant on-site support in the form of boat time, repairs to sampling rigs and access to X-ray facilities. Also, they are subject to hazards that do not assist prediction of service life, such as storm damage to test rigs and vandalism. Furthermore, year-on-year variation in borer recruitment rates and logistical limitations on replication mean that statistical interpretation of tests is difficult. Nonetheless, despite all these caveats, marine trials provide engineers with the best predictors of service life.

To obtain findings that are applicable to the range of conditions under which the wood under test is expected to perform, it may be most economical to establish collaborative testing. This will yield comparable results at a range of sites, whilst control panels will quantify the level of borer challenge at each site and will enable mapping of borer species distribution (Jones *et al.*, 1972; Eaton *et al.*, 1989).

An ingenious test method was designed to measure the sensitivity of the weak link, the settlement phase, to wood treatment. In this, thin treated wood panels at a range of active ingredient retentions were sandwiched between untreated wood. The intensity of settlement on the treated wood revealed the ability of the settling pediveligers to tolerate the level of treatment in the wood, whilst animals settling on the untreated wood, then penetrating into the treated wood, revealed the level of adult tolerance. The teredinid *Bankia gouldi* proved to be much less tolerant of CCA during settlement and metamorphosis than as adults (Johnson and Lebow, 1996). The settlement tolerance level is the crucial level for determining efficacy. By selecting a site where *Sphaeroma* is active, the potential benefits of contact biocides for control of this organism that does not ingest wood was evaluated. Care was taken to expose samples in the intertidal zone where *Sphaeroma* tunnelling is most intense (Eaton and Cragg, 1995).

Marine trials (Fig. 7.18) are expected to last for a number of years, with 5 years being the recommended minimum in the European standard (EN 275, CEN, 1992b) for marine tests (CEN, 1992a,b). Many trials continue for much longer, for example, 16 years of testing acetylated and furfurylated timbers at Kristineberg, West Sweden (Westin *et al.*, 2016), and a 25-year exposure trial with creosote-treated pine and eucalypt at two

Fig. 7.18 Marine testing of wood. (A) Racks of panels removed from the site at Kristineberg for inspection. (B) Panels smothered with fouling organisms, mostly sea squirts (Tunicata).

sites in Australia with high to very high levels of *L. tripunctata* activity (Barnacle and Cookson, 1990), which revealed the importance of timber type with this treatment – eucalypt performed much better than pine (Barnacle and Cookson, 1990). These long-term tests offer greater confidence to engineers regarding likely service life.

Naturally, there is pressure to produce a standardised marine test protocol. In Europe, a testing methodology developed in Sweden (Norman and Henningsson, 1975) eventually became European Norm 275 (CEN, 1992b). This standard uses X-rays to detect teredinid tunnelling within the test samples not visible to superficial examination. The animals tolerate the X-raying and several hours out of water by closing off their tunnel mouths using their paired calcareous pallets (stoppers). The images are formed by the X-ray absorbing characteristics of the calcium carbonate lining of the teredinid tunnels and the X-ray transparency of empty tunnels. Limnoriid attack is assessed as the percent of available surface area covered by their superficial tunnels. Teredinid and limnoriid attack are separately recorded on an arbitrary scale of 0–4 with 0 meaning no attack and 4 meaning sample failed. Control panels generally fail well before the end of the trial period and are replaced at the next inspection.

In selecting test sites, the following considerations are crucial:

(1) A track record at the site of testing activity
(2) The presence of both limnoriids and teredinids
(3) Borer species at the site reflect the borer challenge found in the region
(4) A rapid rate of destruction of untreated non-durable timbers by borers
(5) Good infrastructure support

Sites that satisfy these criteria particularly well include cold-temperate Kristineberg, West Sweden, with *L. lignorum* and *T. navalis*, and warm-temperate Olhão, Portugal, with *L. tripunctata*, *L. pedicellatus* and *T. bartschi*. The Panama sites used by Southwell and Bultman provided notably severe challenge from a wide range of borers (Southwell and Bultman, 1971a,b). The key developed by Ruth Turner is still the most authoritative source for identification of teredinids encountered at unstudied sites (Turner, 1971).

7.3.4 Moisture dynamics

L. Meyer-Veltrup, J. Van den Bulcke†*
*Leibniz University Hannover, Hannover, Germany
†Laboratory of Wood Technology – Woodlab, Gent, Belgium

7.3.4.1 Measurement methods

General aspects

Generally, methods for MC measurement can be divided into direct and indirect methods. Furthermore, they can be distinguished by characteristics like continuous or periodical measurements and measuring local or global MC. Each of these measuring methods has certain peculiarities that need to be considered when designing test setups for bio-based materials and conducting MC measurements in the field.

With the direct gravimetric methods, the MC of the complete test specimen is determined, what can be described as global moisture content (*GMC*). In contrast, the indirect measurement systems, for example, electrical resistance, determine MC at a small location, what can be described as the local moisture content (*LMC*). Consequently, differences in GMC and LMC can occur since capillary effects and diffusion processes within bio-based materials can cause time lags (Meijer and Militz, 2000, 2001). Taking wood as an example, a certain time is needed for capillary water uptake from the end grain of the exposed test specimen (Wagenführ and Scholz, 2008). This liquid water is detected in terms of GMC first, but a certain time span is needed, before an increase in wood MC is detectable as LMC at a certain position remote from the surface.

7.3.4.2 Gravimetric methods – manual

To measure MC gravimetrically, the oven-dry weight of every specimen has to be determined prior to exposure. Alternatively, specimens can be conditioned to constant weight and dried afterwards if loss of volatile compounds or formation of cracks shall be avoided. For every measurement, the exposed samples have to be cleaned from free water and dirt and manually weighed again to determine the MC as follows:

$$\mathrm{MC} = \frac{\left(m_w - m_0\right)}{m_0} \times 100\left[\%\right] \tag{7.6}$$

where MC is the moisture content [%], m_0 is the oven-dry mass [g] and m_w is the wet mass of exposed specimen [g].

Compared with other MC measurement systems, the manual gravimetric method can be conducted without additional and cost-intensive devices. However, the method is extremely time intensive and therefore only advisable for a small number of specimens.

7.3.4.3 Gravimetric methods – load cells

Direct gravimetric measurements can be conducted automatically using load cells, as described by Van den Bulcke *et al.* (2009) (Fig. 7.19). This method is known to be very precise and allows determining the global MC, but not the particular MC at a certain position like critical construction details. Since the method is sensitive to wind and rain loads, an inert reference is necessary.

7.3.4.4 Electrical methods – resistive methods

Electrical resistance measurements are frequently based on the discharge-time-measurement principle. Hereby, a capacitor is charged through a very small ohmic resistance and then discharged through the material to be measured. Based on the time needed for discharging, the resistance of the material can be calculated.

Therefore, stainless steel nails, screws or cables are attached to the specimens to serve as electrodes. The electrodes require a non-conductive covering whereby the tops need to be free to guarantee a top to top measurement (Fig. 7.20).

Resistive methods allow determining the MC at a certain position within a test specimen. Therewith, critical construction details can be assessed. However, since the

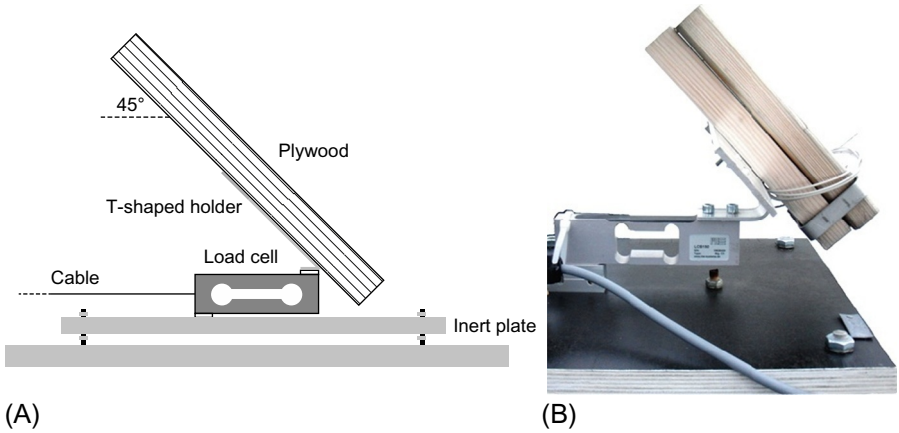


Fig. 7.19 Examples of a load cell measurement. *Left*: Van den Bulcke *et al.* (2009).

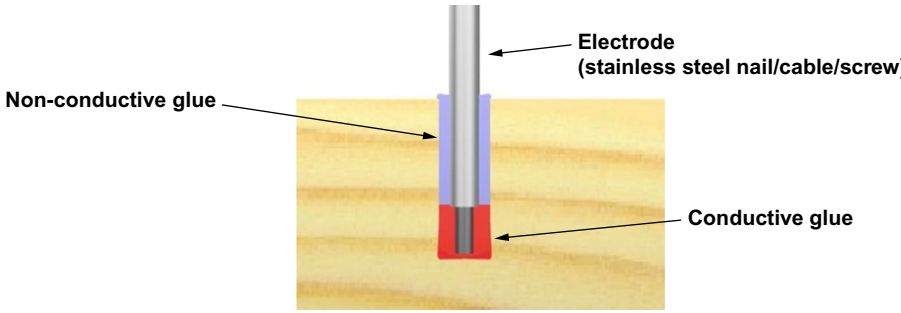


Fig. 7.20 Sectional drawing of an electrode used to determine material resistance.

electrical conductivity depends on specific material properties and material temperature, an additional calibration is needed for every single material. Earlier results showed that measurements with sufficient accuracy on wooden specimens were possible in a range between 15% and 50% MC (Brischke *et al.*, 2008a). Electrical resistance measurements on modified and preservative treated wood resulted in a satisfying accuracy for MC above 15% and even above fibre saturation (Brischke and Lampen, 2014).

7.3.4.5 Electrical methods – capacitive methods

Capacitive or dielectric MC measurements are non-destructive methods (Fig. 7.21). The measurement principle is based on a capacitive electric field. The field forms between the probe head and the respective test material whereby a higher MC leads to a high dielectric constant that increases the capacity. The capacitive method is a relative measurement, which means the test result is given as the difference between the dry and the wet material. Similar to resistance-based MC measurements, capacitive

Fig. 7.21 Examples for handheld capacitive measurement devices.

methods allow determination of LMC. Capacitive measurements, however, suffer from a strong relationship between permittivity and wood density, which is often unknown and varies within a test object.

7.3.4.6 Hygroscopic methods

Hygroscopic MC measurements are based on the relationship between relative humidity RH, temperature and equilibrium wood MC (EMC). From temperature and humidity in a borehole, one can calculate the respective MC (e.g. Evans, 2004). However, this method is only applicable for MCs below fibre saturation.

7.3.4.7 Substitute sensors

If a material under test does not allow an installation of electrodes or boreholes, so-called substitute sensors can be applied (Fig. 7.22). Hereby, the electrical resistance of a known material is measured in a sensor, for example, a dowel made from the known material. With this, the RH and corresponding MC of the unknown material, for example, rotten wood or fibrous material, can be calculated.

7.3.4.8 Imaging

Most imaging methods are confined to the lab (*cf*. subchapter on lab methods), given their size and complexity. Recent developments in mobile NMR (nuclear magnetic resonance) imaging, however, have opened up the possibility to quantitatively and

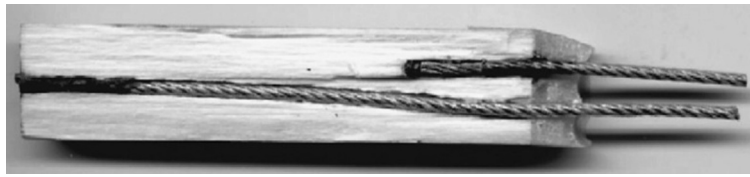


Fig. 7.22 Longitudinal cut through a wooden substitute dowel, containing a pair of glued electrodes (Brischke *et al.*, 2008b).

non-invasively measure the presence and movement of water (Windt and Blümler, 2014). Different groups report on the development of portable systems (Jones *et al.*, 2012; Geya *et al.*, 2013). In most cases, the magnetic field strength is relatively low, thus restricting resolution. This method could, however, be used for in-field studies of moisture distribution in wooden components. For an explanation of the basic principles of NMR, the reader is referred to the chapter on lab methods for MC measurements.

7.4 Weathering and leaching

E. Melcher, M. Humar†*
*Thünen Institute of Wood Research, Hamburg, Germany
†University of Ljubljana, Ljubljana, Slovenia

Wood is susceptible to biological degradation and this process plays an important role within the natural material cycle. As a consequence, timber in wooden constructions can be protected by means of design measures (Leiße, 2002; Štefko and Reinprecht, 2004), wood modification (Hon, 1996; Rapp, 2001; Hill, 2006; Schultz *et al.*, 2008) or wood preservation (Liese, 1954; Nicholas, 1973; Richardson, 1978) to guarantee a designed service life.

Practical experiences and results from field tests show that although wood preservatives can extend the service life of treated timber, detectable loss of preservative components takes place during that time (Nurmi, 1990; Graf *et al.*, 1993; Evans *et al.*, 1994; Lebow *et al.*, 2000; Burkhardt *et al.*, 2007; Melcher and Müller, 2016). Different external factors (Fig. 7.23) resulting in a depletion of preservative components have been reviewed (Hingston *et al.*, 2001).

As long as inorganic substances are used in above-ground applications, evaporation or the effect of UV will, in general, be of minor importance in general. That means that

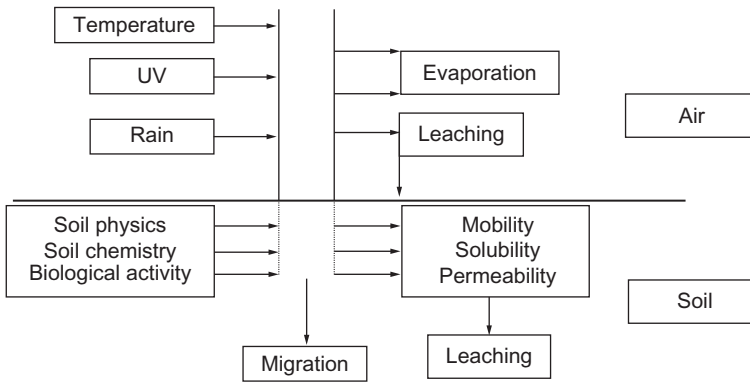


Fig. 7.23 Simplified display of different pathways of preservative components released from treated timber due to external factors.

Fig. 7.24 Partial wetting of the upper surface of a Douglas fir timber tower log (Melcher and Müller, 2016, image: Müller).

the release will mainly occur in case of rain events, provided that there is a sufficient time of wetness (Leicester, 2001). For example, boron leaches from wood, after only a few rain events, if it is not protected by surface coatings (Peylo, 1995). The arrangement of timber within the structure is also of importance as shown in Fig. 7.24, where although the vertical beam is free of snow, the horizontal one is covered on top. Rising temperatures result in melting and enable the water to penetrate the timber. Since this is a slowly occurring process, wood preservative components were displaced deeper into the wood instead of being washed out.

The inner displacement of preservative components (Fig. 7.25) can also occur in test field stakes (Evans *et al.*, 1994 or Liese *et al.*, 2013).

The loss of organic compounds from treated timber can also be due to UV light and temperature, either due to the volatility of the organic compound like tributyltin oxide (*TBTO*) or lindane (Morgan and Purslow, 1973) or decomposed by UV (e.g. iodopropynylbutyl carbamate (*IPBC*)) (Huang *et al.*, 2008; Perdoch *et al.*, 2014). Analysis of old windows revealed that at the end of service life, no organic biocides remained in the old wood frames (Lesar and Humar, 2016). However, if the treated timber is brought into contact with soil, there are a number of parameters that need to be considered like soil physics, soil chemistry or the biological activity in the soil, which may enhance the depletion of compounds. For example, copper-tolerant fungi excrete copious amounts of oxalic acid that react with copper-amine-based wood preservatives resulting in complex compounds that are soluble and thus leachable from wood (Humar *et al.*, 2002).

Creosote is an exceptional case since the loss of this preservative is mainly caused by migration due to gravity (Nurmi, 1990 or Edlund, 1994). Brooks (2001) mentioned that poly-aromatic hydrocarbon (*PAH*) loss rates from creosote-treated wood decline exponentially with time and PAH lost from new and weathered railway ties migrate from the wood into ballast. Such a decline in preservative concentration in treated

Fig. 7.25 Moisture content in an EN 252 (CEN, 2014b) test stake after a certain drying period.

wood occurs during service as has been known for a long time. Therefore, artificial ageing procedures were used in investigations focused on the improvement of the wood preservative performance. Consumer, public and regulatory concerns for the environmental risk of chemical treated wood largely started in the 1970s, although according to Willeitner (1973) this topic was in discussion since Rachel Carson published the 'Silent Spring' in 1962.

The release of wood preservative components to the environment can be examined either in experiments on a laboratory scale or on a field scale using different approaches (Kennedy and Collins, 2001; Waldron *et al.*, 2005; Thaler and Humar, 2014; Bahmani *et al.*, 2015a,b) whereby a number of reviews and surveys were published in this context during the last decades (Cockroft and Laidlaw, 1978; Lebow, 1996; Hingston *et al.*, 2001; Lebow *et al.*, 2004; Ruddick, 2008).

7.4.1 Lab tests

Ruddick (2008) stated that '*it has long been recognized that neither the laboratory testing nor the use of field stakes can adequately assess the performance of treated wood above. Consequently, several new test protocols have been introduced to assess of treated wood in above-ground exposure*'. Although this statement focused predominantly onto the performance of treated wood, it should also be valid for leaching studies.

In order to assess the behaviour of treated wood in service, many laboratory test methods employ ageing procedures based on water immersion tests in general like EN 84 (CEN, 1997a, Fig. 7.26), AWPA E11-97 (AWPA, 1998), CEN/TS 15119-1

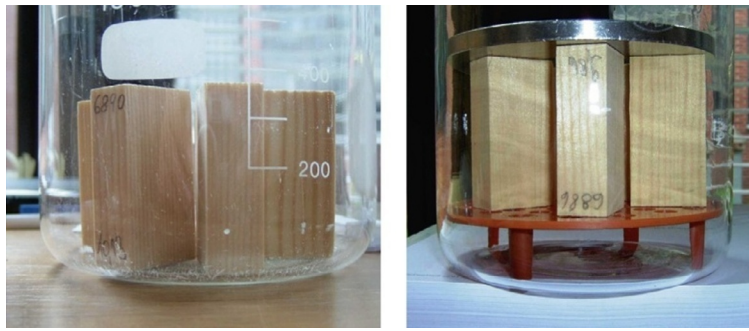


Fig. 7.26 Test set-up according to EN 84 (CEN, 1997a) without water – static (standard) and dynamic *(right image)*.

(CEN, 2008), CEN/TS 15119-2 (CEN, 2012c) or prCEN/TS 16637-2 (CEN, 2013c). The main advantages of lab tests are their simplicity and in principle their reproducibility. Furthermore, lab tests allow the separate investigation of various parameters such as retention (Radivojevic and Cooper, 2007), pH value (Warner and Solomon, 1990; Moghaddam and Mulligan, 2007) or leaching medium (García-Valcárcel *et al.*, 2004). Therefore, it is not surprising that a lot of findings concerning leaching processes have been derived from such experiments especially regarding the calculation of flux rates (Van Eetvelde, 1998; Schoknecht *et al.*, 2004a,b; Temiz *et al.*, 2006; Schoknecht *et al.*, 2009) or modelling (Waldron *et al.*, 2005; Waldron and Cooper, 2010; Lupsea *et al.*, 2013). Besides standard procedures, the leaching behaviour has also been investigated in laboratory scale by means of the shower test (Havermans *et al.*, 1993).

All these procedures share the basic principle of submerging a number of treated wood specimens in a set amount of water for a defined time interval.

The earliest of these were developed to study the chemical interactions between wood and active ingredients, such as standard DIN 52172-2 (DIN, 1972), which prescribes that the wood specimens have to be split into small wood splinters. Even though this standard was not designed for any particular use application, it has been very useful for assessing the copper-chromium binding capability in wood; however, the method is not suitable for assessing the leaching of chemicals from wood in above-ground applications.

The next generation of leaching standard was ENV 1250-2 (ENV, 1995); this standard was the first one to include a short drying period. In the last decade, there has been a considerable public interest in the leaching of toxic chemicals from treated wood. Therefore, a new generation of standards based upon the OECD recommendations (Health and Safety Division Environment Directorate, 2007) have been developed. One standard for above-ground applications, CEN/TS 15119-1 (CEN, 2008), prescribes shorter leaching periods, which simulates short rain events followed by a drying phase, whilst another standard application, CEN/TS 15119-2 (CEN, 2012c), prescribes longer leaching periods, which simulates in-ground leaching, and is based on simple immersion tests. They aimed either on simulating use class 3 (UC 3) conditions through the application of wetting and drying cycles (CEN/TS 15119-1 (CEN, 2008)) or by means of permanent immersion to simulate UC 4 situations (CEN/TS 15119-2 (CEN, 2012c)).

Most relevant aspects affecting leaching behaviour in above-ground situations (UC 3) are wood species, type of wood preservative, impregnation procedure, preservative retention, leaching procedure itself, pH value, penetration depth, dimension and constructional design although the latter three are difficult to assess at lab scale.

7.4.1.1 Lab leaching procedures

Several leaching protocols in lab scale were developed or proposed during the last few decades with a number of them being standardised, leading to question the comparability of the obtained results. As a part of the European project 'Harmonisation of leaching/extraction procedures', Esser *et al.* (2001) examined three existing leaching methods: the diffusion tank test according to NEN 7345, the lab protocol according to ENV 1250-2 and the shower test. Based on the results, they come to the conclusion that during initial leaching periods ENV 1250-2 and NEN 7345 submerged specimens are characterised by a higher depletion rate of heavy metals than was observed using the test with intermittent rainfall. The authors explain this is due to the exposure conditions because not all wood surfaces of the pile subjected to the rainfall test are leached. They also concluded that the shower test is much more relevant for treated wood in above-ground applications (UC 3), whereas the immersion tests ENV 1250-2 and NEN 7345 are applicable to preservative wood used in ground and/or water contact (UC 4) with the preference NEN 7345. However, it is recommended that NEN 7345 should be carried out at a pH around 7 instead of 5 due to the severe leaching conditions.

Habicht *et al.* (2003) compared the European standard EN 84, the Japanese JIS K 1571 (JIS, 1998) and the North American AWPA E11 using three copper-based model formulations. The authors worked out that '*the utilisation of the three ageing protocols lead to different results for leaching rates of copper for the same type of wood preservative*'. This result is to be expected since various parameters of influence (e.g. wood specie or shape of specimens) differ. Regarding the investigated parameters, they concluded that '*the shape of the wood specimen had the biggest influence on the copper leaching rates*'. They demonstrated that the ratio increase of the cross-section to the longitudinal area of the wood specimens from 1:5 (EN 84), 1:2 (AWPA E 11) to 1:1 (JIS K 1571, JIS, 1998) of the cross-section result in copper leaching rates for the CX formulations ranging from 6%–7% (EN 84), 8% (AWPA E11) to 15%–16% (JIS K 1571, JIS, 1998). In contrast to this, the authors pointed out '*that there is no clear concentration dependence of the relative copper leaching*'. Finally, they stated that '*the leaching rates reported in this paper correspond well to leaching data from laboratory trials on copper chromium and ACQ formulations reported in the literature*'.

Schoknecht *et al.* (2003) investigated the loss of wood preservative components by means of a modified EN 84 test in combination with different shapes of samples. They could be shown that '*the percent losses of all investigated substances decrease with a decreasing ratio between the surface area and the volume of the specimens*'. This becomes especially obvious in case of used treated round wood where 51% of boron was leached from copper chrome boron (*CCB*)-treated round wood (∅ 60 mm × 200 mm, area–volume ratio: 0.67) with only an increase in diameter to

120 mm (area–volume ratio: 0.33) causing a decline of boron leaching to 31%. For the typical standard test specimen with a dimension of 15 × 25 × 50 mm and a derived area–volume ratio of 2.13, a total loss of 83% boron was determined. This observation was also made for copper and chromium to a minor extent as well as for benzalkonium chloride and propiconazole. Especially to be emphasised is the conclusion that '*results of leaching experiments might be used for a rough estimation of biocide losses caused by rain*'.

Melcher *et al.* (2004) investigated the leaching behaviour of boron and copper from CCB-treated specimens using EN 84 and OECD (2003) test protocols. Whereas EN 113 (CEN, 1996) wood blocks (50 × 25 × 15 mm) were used in EN 84 tests, the dimension of specimens according to draft OECD guideline corresponded to 150 × 50 × 10 mm. The wood-surface-to-water-volume ratio was set to 40 in both cases. The authors stated that similar depletion rates were determined for copper and boron independent on the leaching protocol applied (Fig. 7.27) whereby about 90% of boron and about 10% of copper was leached in total. Fig. 7.27 also illustrates that the highest boron loss was determined after the first water exchange, whereas for copper it was the second one.

Stook *et al.* (2005) examined the leaching behaviour of pressure-treated timber with different copper-based preservatives by means of 18 h lasting batch leaching tests. The authors stated that the data of these studies are in line with previous results regarding the depletion pattern from CCA-treated wood whereby arsenic and copper leach more relative to chromium. Depending on the batch test applied in total, 1.8%–2% Cr, 3.6%–9.9% As and 6.5%–19% Cu were leached. In general, the highest Cu depletion was found for all tested preservatives so far as the 'toxicity characteristic leaching procedure' (*TCLP*, EPA Method 311) was applied. If preservatives with an organic cobiocide were tested, it might be vice versa for the cobiocide. Copper-citrate-treated wood that was subjected to TCLP resulted in a citrate loss of 12%, whereas in case of the 'synthetic precipitation leaching procedure' (SPLP, EPA Method 312) 37% citrate were leached for example.

Lesar *et al.* (2008) compared the leaching of copper and boron compounds from wood, impregnated with two different wood preservatives according to the three different standards: SIST EN 84, SIST EN 1250 and OECD recommendation (OECD, 2007) (Fig. 7.28).

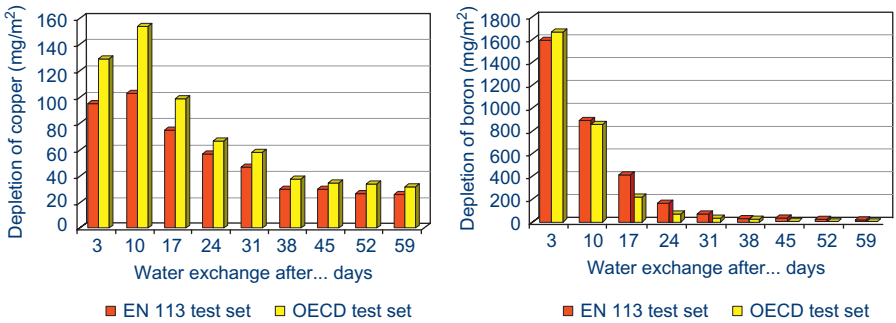


Fig. 7.27 Depletion of copper *(left graph)* and boron depending on the applied test design according to Melcher *et al.* (2004).

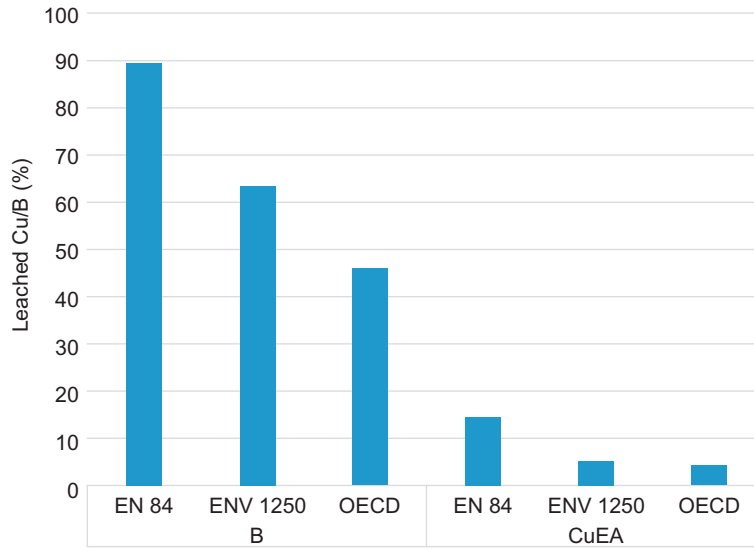


Fig. 7.28 Influence of leaching procedure on leaching of Cu and B from wood impregnated with copper-amine-based preservative solution consisting of copper, ethanolamine, boron and quaternary ammonium compound.
From EN 84 (CEN, 1997a), ENV 1250 (ENV, 1995) and OECD (2007).

There were two types of preservatives used. The first one was alkaline copper quaternary (ACQ) type of copper-based wood preservative based on the copper, ethanolamine and quaternary ammonium compound. The second solution was a mixture of boric acid and quaternary ammonium compound. They found that the '*highest portion of leached biocides were determined according to the SIST EN 84 procedure, the lowest portion according to OECD recommendation*'. This is in line with MC data as well. The highest moisture was determined at water-saturated EN 84 samples, followed by ENV 1250, and the lowest MC was determined at specimens leached according to OECD guidelines. Additionally, at all three tests applied, that highest leaching was determined in the first stages of leaching. It seems likely that, in the first periods of decay, deposits from the surface and weakly bound biocides are leached. Furthermore, the authors stated that '*all three methods applied on various preservative solutions, give us the same ranking of wood preservatives regarding the amount of emitted active ingredients*'.

Similar data were reported in the field studies performed by Thaler and Humar (2014). The cited authors investigated the copper depletion from copper-ethanolamine-treated wood by means of the following standardised leaching protocols ENV 1250-2, CEN/TS 15119-1 (CEN, 2008) and CEN/TS 15119-2 (CEN, 2012c). They observed that regardless the initial copper content of the treated samples the highest metal content was analysed in leachate after the first water exchanges. Furthermore, they pointed out that the percentage copper loss was two times higher for test sets with a lower preservative content compared with the other.

7.4.1.2 Influence of pH

It is known that both inorganic and organic acids can increase the depletion rate especially of inorganic wood preservative components (Warner and Solomon, 1990; Cooper, 1991; Honda *et al.*, 1991; Wang *et al.*, 1998; Hingston *et al.*, 2001).

Beside the pH value of the leaching medium, the corresponding anion has to be taken into account because these can react with preservative components, leading to the formation of insoluble precipitates (Stephan *et al.*, 1996; Sierra-Alvarez, 2007). Moghaddam and Mulligan (2007) could show, for example, that at a pH of 3 the depletion of chromium from CCA-treated wood increases from 5.6% to 47.2% if sulfuric acid is used instead of nitric acid. An identical observation was made for copper (from 70.8% to 104.5%) and arsenic (from 51.8% to 82.7%). It has also been reported that humic acid, oxalic acid and acetic acid can form soluble complexes with copper-ethanolamine or copper-chromium complexes (Humar *et al.*, 2002). As these complexes are soluble, they can easily diffuse from wood. A similar effect was reported in the locations with very acidic rain.

7.4.2 Field tests

The investigation of the leaching behaviour of active ingredients from treated wood in field trials is more realistic and challenging, because different parameters affect the depletion simultaneously. In principle, two test setups are commonly used, with both of them carried out either using smaller specimens (commonly applied) or by means of practical dimensions/objects (Wischer and Willeitner, 1977; Nurmi, 1990; Peylo and Willeitner, 1999; Lebow and Foster, 2005; Thaler and Humar, 2016). It is also important to distinguish how the emission is determined – directly or indirectly? The direct method is based on the collection of the leachates, for example, from impregnated wood exposed in UC 3 – out of ground contact (Morsing *et al.*, 2010). The leachate can be bulked or separately collected for each sample. This test gives information about leaching dynamics and can be directly linked to the climate data. A typical example of this kind of test is shown in Fig. 7.29.

The indirect procedure takes into account that difficulties occur in the collection of emissions (leachate) from the timber exposed in ground contact (UC 4). Therefore, these test designs are usually based on destructive sampling measures from exposed material. Due to experimental expenditure in analytical sample preparation, often borings or small stake segments (Evans *et al.*, 1994) were taken from the exposed treated material after certain time intervals, digested and analysed in order to determine the remaining preservative content, although it is well known that the distribution of preservative can differ due to the preservative used (Jüngel *et al.*, 1998) or the exposure conditions (Evans *et al.*, 1994), for example. Consequently, a complete sampling (Fig. 7.30) as performed by Melcher and Wegen (2000) should be a method of choice. This becomes obvious if the remaining contents of individual segments were compared with the remaining content of the whole stake. In segments 6 and 7 of stake pressure treated with a copper-based formulation after 7 years of exposure in ground contact, they determined a remaining copper content of 29% and 35%, respectively, whereas for the whole stakes a remaining copper content of 54% was derived.

Fig. 7.29 Test design for vertical and horizontal exposure according to CEN/TR 16663 (CEN, 2014f).
Courtesy of R. Wegner, MPA Eberswalde.

7.4.2.1 Testing above ground – UC 3

Morsing *et al.* (2010) investigated the leaching behaviour of copper-boron pressure-treated wood over 7 years by means of a vertical test design as it is shown in Fig. 7.29. They could demonstrate that after the first month 15.4% of the boron and 2.3% of the copper were leached, whereas at the end of the test 25.3% boron and about 8.0% copper were released. Lab tests according to CEN/TS 15119-1 (CEN, 2008) that were performed in parallel result in higher depletion rates (25.7% for boron and 4.6% for copper after 22 days) and an unrealistic predicted depletion rate of 230% boron after 2 years of exposure.

A similar test design for above-ground testing was used by Schoknecht *et al.* (2004a). They found that the mean daily propiconazole flux rate is with 0.7 mg/m^2/day in the same magnitude as it was calculated for the lab test for the first 60 days according to guideline 1 (mean 1.35 mg/m^2/day) with 3 immersion events of one minute per day. After 210 days of exposures with 85 rainy days, a cumulative loss of 150 mg propiconazole per m^2 was determined, which fits with the loss of propiconazole (60 and 240 mg/m^2 in field tests depending on the orientation of the test racks) obtained for specimens exposed for 240 days with 480 mm rain (Morsing and Lindegaard, 2004).

Under certain circumstances, a deviated leaching behaviour of organic active components can occur due to UV-light-induced chemical reactions resulting in various decomposition products. Volkmer and Schwarze (2008) observed a minor IPBC content in base coat already after 6 months of exposure, which was explained by the known low UV stability of this biocide. This possibility requires a higher analytical expenditure in order to close the material balance.

Surprisingly, leaching of copper from wood in above-ground applications could be very severe as well. From Fig. 7.31, it can be resolved that copper leaching rates after 42 months of exposure are comparable to leaching in ground.

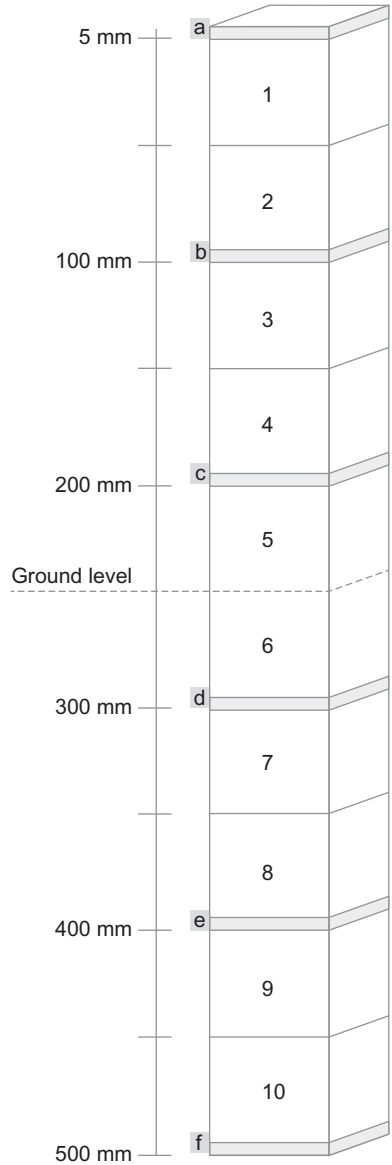


Fig. 7.30 Simplified display of a partial (*grey and black letters*, e.g. Evans *et al.*, 1994) and complete sampling *(numbers)* using an EN 252 (CEN, 2014b) stake.

However, this cannot be true for all above-ground applications. Some exposures in use class 3 are more exposed to wetting than the others. This can be clearly seen in Fig. 7.32. First of all, it can be stated that the highest MC was detected in the upper area (top) of sapwood in all cases. However, the mean MC in the upper area of the North beam is approximately twice as high as that of the East beam or of the underside

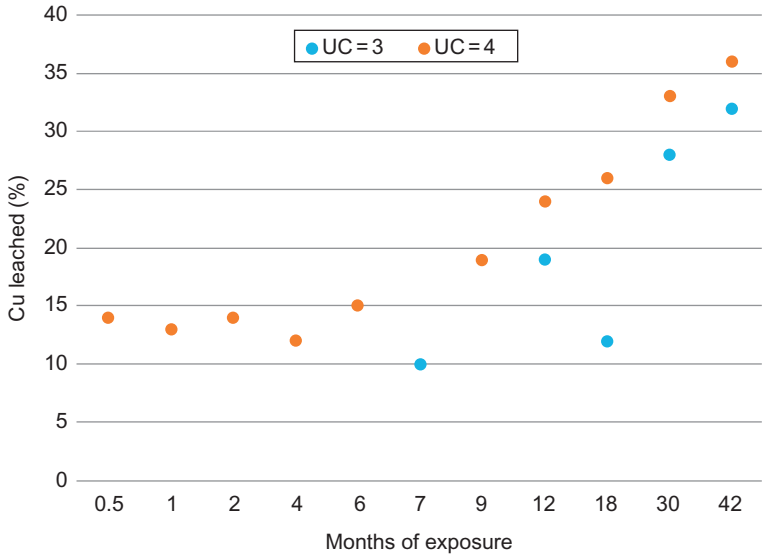


Fig. 7.31 Leaching of copper from copper-ethanolamine-treated wood as a function of exposure conditions and time.

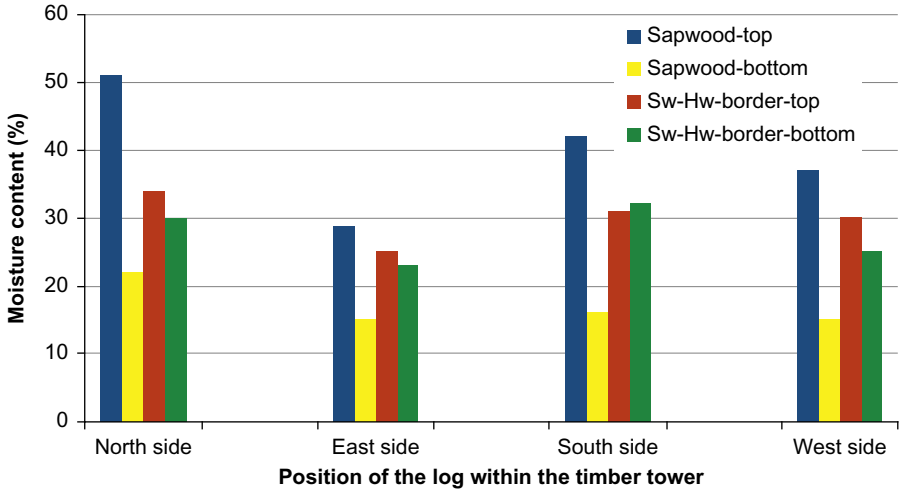


Fig. 7.32 Mean moisture content in Douglas fir logs exposed in UC 3 depending on their position in the timber tower and measuring point (*Sw*, sapwood; *Hw*, heartwood) (Müller *et al.*, 2015).

of the North beam. Furthermore, it is remarkable that MCs close to the heartwood were measured ranging from around 25% to 35%.

A comparison with the Cr–Cu ratios in Table 7.8 shows that nearly identical Cr–Cu ratios (1.71 and 1.74) were determined at the bottom of stem disc OS 1 and ON 1 compared with freshly treated EN 252 (CEN, 2014b) stakes. It can be deduced that, at these places, no leaching took place and consequently the initial concentration should remain.

Table 7.8 Copper and chromium content in EN 252 (CEN, 2014b) stakes treated with a commercial CC salt depending on the basis of calculation according to Liese *et al.* (2013)

Material	Content based on analysis of the treating solution (kg/m^3)		Content based on stake analysis (kg/m^3)	
	Cr	Cu	Cr	Cu
Commercial CC containing wood preservative				
EN 252: pine	1.95	1.13	1.94	1.12
Cr–Cu ratio	1.73		1.73	

7.4.2.2 Testing in ground – UC 4

In-ground leaching of wood preservative components is a rather complex process, because it is influenced by several abiotic and biotic aspects like pH of the soil, MC, soil composition, climate (e.g. Lebow, 1996; Schultz *et al.*, 2000 or Schultz *et al.*, 2002) and in case of organic biocides a possible photoinduced decomposition (Takahashi *et al.*, 1985) or degradation caused by non-target micro-organisms (Chaudhry and Chapalamadugu, 1991; Dubey and Roy, 2003; Jacobs-Schönwandt *et al.*, 2010). The major problem, however, is the soil itself, because direct sampling of the leachate becomes impossible. Therefore, the depletion is assessed indirectly by determining the remaining content of the exposed test specimens after a certain time. Since this procedure implies destructive sampling measures only discontinuously, few data can be generated, or a large number of test specimens are required.

One of the main factors that have considerable influence on the copper leaching from treated wood is humic acid (e.g. Cooper *et al.*, 2001). Leaching of CCB (Cu-, Cr- and B-treated wood) resulted in ten times higher copper leaching, compared with the specimens leached with distilled water. Firstly, humic acids may initiate the inversion of the chromium fixation process. Some researchers (e.g. Evans, 1987 or Cooper, 1991) reported already that high acidity may be the key to 'mobilise' copper in wood. Furthermore, humic acids contain many organic functional groups such as carboxylic, phenolic, hydroxyl, amine and quinone groups, which provide a number of different potential binding sites for metal ions (Chen and Wu, 2004). As a consequence, soluble complexes between copper and humic acid are formed, which results in increased leaching as well.

Therefore, leaching from degraded and non-degraded parts of the three poles was compared. The poles were made of Norway spruce and treated with copper-ethanolamine-based wood preservative. After 5 years of use, severe brown rot degradation developed on one-half of the poles (Fig. 7.33).

The poles were split, and copper distribution and compression strength (as a measure for degradation) were determined. From data in Table 7.9, it can be clearly seen that the degraded part had considerably lower compression strength (material was too degraded to prepare samples for bending strength testing) than non-degraded parts of the poles. Furthermore, from the analysis of copper retention and distribution, it can

Fig. 7.33 Cross-section of the pole after 5 years in service, with clearly visible decay on the one side of the pole.

be clearly seen that spruce poles were only shell treated. Shell treatment resulted in insufficient performance of treated poles. However, additional information that can be resolved from Table 7.9 is a fact that copper concentration in the degraded part was considerably lower than in the non-degraded part.

It should be considered that copper retention in degraded wood is overestimated; as the wood was degraded, retentions of copper would be lower if expressed in m/V instead of m/m. However, there is an open question if copper concentrations in degraded parts are lower because of degradation-induced translocation to the environment or degradation developed as a result of these parts of the wooden poles being incorrectly treated. The authors believe that leaching because of fungal infestation is a predominant reason for the described copper leaching. The mechanisms of copper translocations are active transport through hyphae and/or formation of soluble complexes between organic acids excreted by brown rot fungi that diffuse from wood.

Although it is difficult to compare the outcome of leaching tests due to the variability of parameters of influence, the following tendencies can be derived: The percentage depletion of copper from CC-, CCA- or CCB-treated wood is greater in ground than that of chromium (Evans and Edlund, 1993; Breslin and Adler-Ivanbrook, 1998; Melcher and Wegen, 2000; Wakeling, 2006; Humar *et al.*, 2014).

The majority of loss occurs within the first month of exposure, after which a steady state is achieved regarding a nearly similar percentage of leaching of chromium and copper indicated by an identical Cr–Cu ratio.

Lebow (1996) cited that '*Southern Pine decking lost approximately 5 percent of CCA components and 8 to 10 percent of copper from ACQ–B treated wood during exposure to 80 in. (2,032 mm) of rain during 20 months (Fox and others, 1994). The majority of leaching occurred during the first 20 in. (508 mm) of rainfall*'. Remarkably, Humar *et al.* (2014) determined the majority of leaching occurred within the first 8 months, with approximately 570 mm of precipitation (Tables 7.10 and 7.11). After that exposure time, the authors could not observe a real change in the Cr–Cu ratio, and therefore, they assume that a steady state had been achieved. Beside this, they mentioned that Jin and Preston (1993) also observed this change between 6 and 9 months of exposure.

Table 7.9 Distribution of copper (mg/kg) and compression strength in degraded and non-degraded post parts after 5 years in service

	Non-degraded part				Degraded part			
	Section							
	c_{Cu} (mg/kg)				c_{Cu} (mg/kg)			
Post 3 years	0–2 mm	2–7 mm	7–12 mm	F_m (N/mm^2)	0–2 mm	2–7 mm	7–12 mm	F_m (N/mm^2)
A	1644 (296)	925 (261)	469 (241)	49.2 (3.2)	1008 (70)	510 (112)	129 (32)	21.7 (8.4)
B	1931 (90)	693 (200)	223 (105)	39.1 (3.0)	1473 (70)	619 (93)	197 (80)	10.2 (9.0)
C	1001 (167)	118 (40)	33 (20)	38.1 (4.2)	647 (62)	107 (37)	64 (12)	27.7 (9.1)

Standard deviations are given in the parenthesis. Degraded and non-degraded part can be resolved from Fig. 7.32.

Table 7.10 Influence of time on leaching of Cu and Cr from CC-treated EN 252 (CEN, 2014b) pine sapwood stakes exposed in UC 3 in Hamburg, Germany (Humar *et al.*, 2014)

Time of exposure (month)	Metal content before exposure (mg)		Metal content after exposure (mg)		Derived loss		mm/m^2 precipitation (days)	Cr–Cu ratio after exposure
	Cr	Cu	Cr	Cu	Cr mg (%)	Cu mg (%)		
0	610	351	610	351	–	–	–	1.74
4	636	371	626	353	10 (2)	18 (5)	403	1.77
8	621	362	588	312	33 (5)	50 (16)	168[a] (39)	1.88
12	630	365	624	337	6 (1)	28 (8)	256 (55)	1.85
16	636	371	574	305	62 (10)	66 (18)	258 (63)	1.88
20	627	365	612	321	15 (2)	44 (12)	316[a] (71)	1.91
24	624	362	607	328	17 (5)	34 (9)	221 (69)	1.85

[a] Sometimes as snow.

Table 7.11 Influence of time on leaching of Cu and Cr from CC-treated EN 252 (CEN, 2014b) pine sapwood stakes exposed in UC 4 in Hamburg, Germany (Humar *et al.*, 2014)

Time of exposure (month)	Metal content before exposure (mg)		Metal content after exposure (mg)		Derived loss		mm/m^2 precipitation (days)	Cr–Cu ratio after exposure
	Cr	Cu	Cr	Cu	Cr mg (%)	Cu mg (%)		
0	601	349	601	349	–	–	–	1.72
4	636	371	658	365	–	6 (2)	403	1.80
8	621	362	577	294	44 (7)	68 (19)	168[a](39)	1.96
12	630	365	597	309	37 (10)	66 (18)	256 (55)	1.93
16	636	371	557	283	79 (21)	88 (24)	258 (63)	1.97
20	627	365	579	290	48 (8)	75 (21)	316[a](71)	2.00
24	624	362	593	305	31 (9)	57 (16)	221 (69)	1.94

[a] Sometimes as snow.

7.4.3 Summary of weathering and leaching

Leaching of active ingredients from wood is one of the most important criteria for the assessment of wood preservatives followed by efficacy against target organisms. Unwanted emissions decrease the performance of treated wood and have a negative influence on the environment. Therefore, leaching studies attract a lot of attention in the wood science community. Although it is a consensus that laboratory and field leaching tests are characterised by minor practical issues, both have their uses. The advantages of laboratory tests are their simplicity and reproducibility and especially the option to investigate each parameter separately. When interpreting laboratory tests, the absolute values are less significant than the rankings of tested formulations. Field tests, however, allow the assessment of the performance in general. Unfortunately, long-lasting field leaching experiments are rare.

7.5 Monitoring of structures and in-service testing

F. Lanata, N. Macchioni†, S. Palanti†*
*ESB, Nantes, France
†CNR IVALSA, Trees and Timber Institute, Sesto Fiorentino, Italy

7.5.1 Introduction

In previous chapters, bio-based materials used in building were already sorted into wood-based products, wood derivatives and non-wood materials. When discussing building efficiency, building monitoring and in-service testing of buildings, we can also divide bio-based materials according to their principal purposes, that is, structural materials and division/insulation materials.

This type of categorisation is much more functional when one must speak of monitoring and in-service testing, since the activity is to be designed and put in place depending on the materials used rather than their nature. A structural element should primarily be able to withstand the stresses independently from the material, whether it be of steel or of wood.

For structural materials, only wood, both as solid wood and structural engineered panels (glulam, cross laminated timber (*CLT*), laminated veneer lumber (*LVL*), oriented strand board (*OSB*) etc.), can be considered as a bio-based material. Presently within the building markets, wood derivatives are among the most common insulating materials, for example, wood-wool panels, in competition with non-bio-based materials like mineral wool. However, sheepswool is acquiring importance as a natural insulating material, together with other lignocellulosic composites like straw or reed.

In this section, *monitoring* will be considered in order to early assess the attacks by organisms that cause decay of materials, as decay will have a negative effect on the properties of both structural and insulation materials.

The *in-service tests* will serve to deeply analyse structural elements following the monitoring results, in order to assess their actual residual performance.

In fact, the durability of a building can be defined as the property of lasting for a given or long time without breaking or getting weaker; thus, if the building is of bio-based materials, the durability of such a building passes through the durability of the composing materials. Monitoring and in-service testing are aimed at lengthening the life cycle of bio-based buildings through the early assessment of the presence of any agent of degradation, in order to counteract their activities and limit their effects.

The literature (e.g. Frühwald *et al.*, 2008) reports that the pathology of most of wooden buildings was generally caused by an insufficient durability, low level of knowledge of the material, poor assembly and, more, specifically too high a MC. Similar problems may exist within hybrid building systems, where poor design between bio-based and non-bio-based materials may lead to future issues in performance.

As reported earlier, both insects and fungi can degrade bio-based building materials. The presence of high MCs within the materials can facilitate the attack by insects, especially of termites, recognised as the most structurally dangerous insects, and it is an essential requirement for fungal attack. The MC is a condition *sine qua non* for developing a biotic attack, and for this reason, the monitoring during the service life is an adequate measure to limit it. But this is true only for fungal attacks, because for insects, Coleoptera and termites, the main risk factor remains the local hazard; in this case, the moisture measurements are not sufficient to limit them. The distribution of termites in urban areas in Europe shows that the importance of the attacks is evident not only in Mediterranean countries but also around the urban areas of Central Europe, particularly in France (Clément *et al.*, 2001).

The section describes the monitoring methodologies of both humidity and MC, in terms of how and where. Some issues are also presented regarding mechanical stresses and insect monitoring. The moisture measurement is rather punctual and refers to a strictly local value; thus, the positioning of data loggers is crucial and must take into account the presence of possible moisture traps (e.g. bathrooms) or basic structural joints.

In modern timber houses, the wood itself is no longer visible, both from outside and from inside. Due to fire safety, wooden elements are covered by fire-safe panels that make it difficult for visual inspection and direct checking of wet areas. Therefore, monitoring through inspection windows, already considered as a basic part of the evaluation, becomes essential. The allocation of inspection windows during house building is not currently common, but it could represent a simple solution to limit future failures. Within this framework, a monitoring system – well designed and properly implemented – can actually bring added value in streamlining the work of maintenance and to an extension of the useful life of the building (Luchetti, 2016).

Banks and insurance companies have a key role in the building industry and market, through funding of the construction of new buildings and in helping to purchase homes. Often, the building itself is the guarantee for financing, but there may be cases where the building's life can be compromised by the use of inappropriate materials and techniques in the design. Currently, the financial institutions that provide these services do not generally insist on thorough validation of the project quality, assembly or monitoring. In the future, this may be legislated for, but in the meantime, it is advisable that evaluation methods be developed by real experts on the use of bio-based materials in buildings.

7.5.2 Monitoring

7.5.2.1 Design standards overview

Moisture and temperature are two key environmental parameters that determine the possibility of mould and rot growth within buildings, which can affect the performance of bio-based materials. Indeed, considering buildings, it is very difficult to control sources of oxygen, stop infestation sources or control temperature beyond those for fungal growth. One option is to control moisture, if possible, and moisture and temperature measurements can be used to follow variations over time. Usually, fungal growth is considered to be possible between 35% and 50% MC and between 25 and 33°C. It is worth noting that the amount of time the material is exposed to these conditions is also crucial (Johansson *et al.*, 2013). The natural environmental conditions of relative humidity and temperature are seldom constant over long periods of time within a building. Instead, they vary over time, with both favourable and unfavourable conditions for fungal growth, However, it is verified that both the mean relative humidity that a building material is exposed to (governing the growth rate of fungi) and the total time that a material is exposed to favourable conditions (when it fluctuates) are not the critical factors. Instead, the duration of both favourable and unfavourable conditions is decisive. Therefore, using the sum of periods favourable for growth, or the mean relative humidity, will not give a realistic prediction of fungal growth. Additionally, it is verified that temperature variations do not have the same effect on growth as alternating the relative humidity.

In textbooks on timber design (Larsen and Enjily, 2009; Porteous and Ross, 2013; Thelandersson and Larsen, 2003), it is often noted that the moisture sensitivity of wood materials needs to be taken into account and that structural timber should be dried (or conditioned) down to an average MC that corresponds to the expected climate conditions found during the service life of the wood product. For example, if wood is put into service with an average MC over 20%, its resistance will be 20% lower than the same wood, at the same loading conditions, put into service with an average MC around 15%. The same MC conditions can result in deformations 45% higher than dried wood. Nevertheless, in European standards, all the mechanical characteristics used for design are given at a reference MC of 12%. A correction factor to take into account the real MC during construction is possible only for solid wood, to reduce commercial sections given at 20% of MC. Properties of other bio-based products are only considered in terms of their reference MC because of the production processes involved.

In Eurocode 5 (CEN, 2004) rules for ultimate limit state (*ULS*) design, the MC and loading-duration effects on strength properties of timber and wood-based products are dealt with using the modification factor k_{mod}. The values of this factor are based on three service classes, representing different climate conditions, and on five different loading-duration classes. For both solid timber and glue-laminated timber, the k_{mod} values are similar for service classes 1 and 2 despite the differences between these two classes in terms of climate conditions. For service limit state (*SLS*) design, the moisture cyclic effects on long-term deflection caused by creep are accounted by means of factor k_{def}, which predicts the larger deflections occurring in more humid

environments. This factor considers a constant MC over the section, which is unrealistic. The problem here, however, is that natural movements (shrinking and swelling) during the service life of wood materials can generate complex stress profiles (over the cross-section) that should be taken into account in the design of timber structures. In any case, the MC is considered as an added load on the structure at design phase.

Prolonged exposure to moisture during construction can also have an impact on the MC of bio-based materials that can negatively affect the products durability and the long-term structural behaviour. Therefore, real in-service conditions are usually unknown and can often be very far from design hypotheses, particularly in terms of environmental conditions and service classes to use in Eurocode approaches. An accelerated degradation has been observed when environmental parameters are not correctly taken into account at design phase.

As it is quite difficult to completely account for environmental variability in the design phase, a complementary approach should be used, comprising properly designing structural details and following the in-service behaviour under environmental loadings, through monitoring and non-destructive testing. All the issues related to the protection and maintenance of bio-based materials structures should already have been considered during design process. Most of the solutions proposed in the literature to prevent deterioration of bio-based materials dealt with water: design details to avoid water accumulation and to allow the structure to dry out quickly and controlling moisture during construction and in-service conditions are the fundamental aspects to take care of to ensure the designed durability. This means that design for durability begins with an understanding of moisture loading and how this interacts with building materials. Where does water come from? How is it transported? How can it be controlled? How can it be removed? The following paragraphs will describe some techniques to measure and control the MC of timber over time and will give some examples of monitoring and non-destructive testing (*NDT*) on timber structures.

7.5.3 Moisture content monitoring

7.5.3.1 Moisture content assessment

There are known difficulties and limitations to model the hygrothermal behaviour of bio-based materials by only using a Fickian model, particularly under high relative humidity and transient conditions (Engelund *et al.*, 2013). Laboratory tests have shown that moisture transport appeared to be blocked or delayed when a series of smaller relative humidity charges was used compared with larger changes. Most of the literatures on computational modelling have been mainly based on laboratory measurements. Recently, some in-field applications have been performed to assess the MC of full-scale elements and in-service bio-based structures.

Rainwater, especially wind driven, is the moisture source that most impacts the performance of the envelope. The amount of wind-driven rain that impacts a building envelope can be measured using suitable gauges, estimated by semi-empirical equations or simulated by more sophisticated computational fluid dynamics modelling. Such studies aim to correlate the wind-driven rain impact to surface degradation

phenomena, such as moisture penetration and biodeterioration, and eventually, its influence on indoor conditions. The extent of the influence of the wind-driven rain on envelope performances has remained to a large extent anecdotal, due to a scarcity of in-field observations and experimental work.

To fill the gap between theoretical and laboratory approaches and real in-service observations, analyses on the monitoring of existing full-scale buildings are starting to give interesting feedback. For example, timber frames have been studied particularly regarding the envelope performances. The timber product that has been investigated the most in recent years is cross-laminated timber panels (CLT), from a mechanical and hygrothermal point of view. Glue-laminated buildings also give interesting results on the mechanical and hygrothermal behaviour. Finally, the monitoring of timber bridges during their service life has shown to be fundamental for the optimisation of the maintenance plans of these structures.

To measure the MC of wood for in-service real structures, the oven-drying method cannot be used (EN 13183-1, CEN, 2002a). Two main techniques have been developed to assess the MC of timber structures: both are local measurements and allow to calculate the wood MC indirectly via modeling approaches using air temperature and relative humidity data (through air temperature and relative humidity) or physically (through the correlation with electric resistivity). Both measuring networks have to be connected to data logger devices to collect all the measuring channels and storage and transfer all the data. In the following, the main advantages and applications of the two methods will be detailed.

7.5.3.2 Indirect environmental modeling moisture measurement

In this case, MC of timber is a function of both the relative humidity and temperature of the surrounding air, in such a way that the theoretical equilibrium moisture content (EMC) is defined at the moment in which the timber is neither gaining nor losing moisture. Different relationships exist in the literature between the EMC and the air temperature and relative humidity. The advantage of the indirect method is its simplicity and the possibility to compare different existing experimental relationships. The MC is assessed by assuming the timber to be in equilibrium with that climate, which is only true under static conditions. For such applications, the accuracy for the RH measurements should be around ±2%–3% and the accuracy for the temperature measurements is suggested to be around ±0.5°C. Measurement frequencies can vary approximatively between one to 15 min, according to the application. Usually, to cut off daily peaks, all the analyses are performed in terms of daily or weekly mean values.

For solid wood or glue-laminated buildings, the MC can easily be assessed on the surface of the structural elements. The MC values can be strongly influenced by the daily variations that are observed at the surface of a structural element, in particular, those exposed to outdoor conditions. It should be noted that short-term fluctuations tend to influence only the surface because the penetration depth of moisture in wood materials is estimated around 3 mm during daily humidity variations (Hameury and Lundstrom, 2004). For indoor elements, the measurement is much more representative because the daily variations of air temperature and relative humidity are not significant. For structural timber elements, it is mainly the long-term EMC that can

be correctly assessed with this method, though the technique is not usually used for periodic monitoring applications.

Inside the walls, the MC can be assessed through different insulation layers, to be able to assess the MC gradient inside the wall and evaluate its performance over time. In this case, T/RH sensors toned to be relatively small in order to not affect the measurements. The monitoring of air temperature and relative humidity in outer walls is usually considered as fundamental in the case of non-conventional assemblies. For some designs, the continuous following of their conditions can allow assessors to evaluate if a risk really exists, assure the insurance companies, provide feedback for further buildings and add the non-conventional design into standard solutions, if pertinent. This is, for example, the reason why the multistorey residential housing at Limnologen, in Sweden, has been equipped with air temperature and RH sensors at six different locations in the building (Serrano *et al.*, 2014). The non-conventional wall assembly comprises the use of a non-ventilated façade covered with cementitious cladding or wood panels. In addition, there is no vapour barrier (plastic film) in the external walls. The structural leading element is a three-layer CLT panel (Fig. 7.34A). The assembly may lead to higher levels of RH, which could increase the risk of mould growth and rot. The 5 years of continuous monitoring undertaken on this building have shown that, during the first months of the measuring period, the RH was considerably higher than the RH in the following period. This higher initial RH is believed to be due to moistening during the construction phase (cementitious cladding) and to the timber being delivered at a MC higher than the EMC. This is confirmed by the calculated theoretical MC of the CLT panels, which showed a substantial drying out, from approximately 15% to approximately 7% during the first months after construction (Fig. 7.34B).

The interest in MC assessment is also related to the in-service use of the building, for example, in the case of rooms in direct contact with water (bathroom, kitchen and shower). For example, CLT panels are produced for structural use in service classes 1 and 2, in accordance with Eurocode 5. The use of CLT panels in service class 3 (MC higher than 20%) cannot be admitted, due to the high level of stressing in glue lines, and

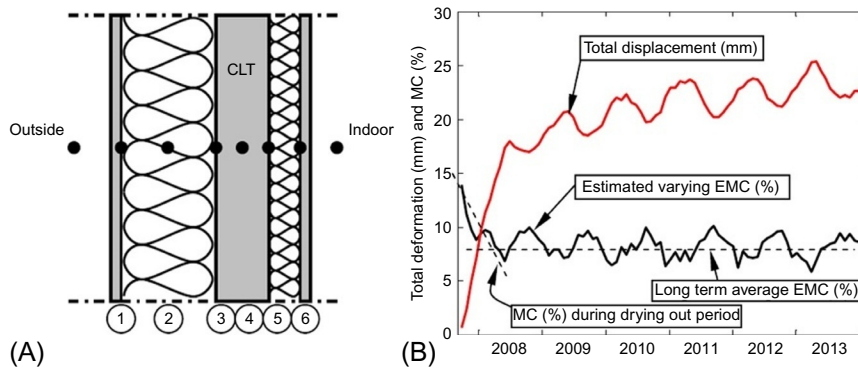


Fig. 7.34 (A) Location of RH and temperature sensors across a CLT wall assembly and the (B) estimated equilibrium moisture content (EMC) of the CLT panels along time (Serrano *et al.*, 2014).

to date, no producer has yet certified it for this service class. Moreover, the French Avis Technique (CSTB, 2012) does not allow the use of CLT panels in swimming pools due to high hygrometry, even for service class 2 conditions. Nevertheless, crosslaminated timber panels are nowadays used across Europe, sometimes with a non-conventional use, as in the case of a building in Almada, Portugal, integrating a 25 m indoor swimming pool and a gymnasium (Jorge and Dias, 2013). The dimensional stability of the CLT panels is being followed since construction, because of the high moisture environment. The design choice has been to leave the timber panels visible to allow an easier visual check of structural elements' response to this particular environment. In any case, a surface protection with water-repellent products is recommended to retard the surface moisture variations due to seasonal and daily changes. In order to guarantee the desired penetration of the preservative product, pine species was used as an alternative to most common spruce timber panels. In addition, it is suggested to coat all places in direct water contact with waterproof membranes. Regarding the main concern of the designer, related to the use of such panels into this high moisture environment, there were no visible pathologies appearing after 4 years from construction. Fungal attack and deterioration were not observed within the whole building, despite the fact that disfiguring fungi or decay fungi could be expected in use class 2, as referred in EN 335 (CEN, 2013b). Mechanical ventilations and control systems are key elements in this type of construction, and long-period stops of this equipment, due to non-operational periods of the swimming pool, should be carefully evaluated and monitored.

7.5.3.3 Physical moisture measurement

For physical determination of the MC, several measuring systems are available, using the principle of resistivity measurements (correlation of wood MC with electric resistivity, according to EN 13183-2 (CEN, 2002b)), measurement of the dielectric coefficient (according to EN 13183-3 (CEN, 2005b)), the absorption of microwaves and optical systems, based, for example, on near-infrared spectroscopy (*NIRS* (Sandak *et al.*, 2015)).

Measuring the electrical resistance of timber is a widely used method to locally evaluate its MC and fit to long-term monitoring purposes. The principal advantages of the electrical method are speed and convenience: very little time is required, and the electrode needles only minimally damage the structural element. Even if literature has shown that the average MC from the readings is within 1% of the true average for values below 30%, this is only true in the case of a correct use of the method. The electrical measurement varies according to the species and to temperature, though optimal conditions for fungal growth tend to be towards the maximum measurable limits of instruments. Therefore, it is important to be able to make species corrections to have reliable measurements. When possible and in the case of uncommon species, it is recommended to make preliminary tests to assess the density of the species used in the building and the real MC of a sample measured through the oven-drying method. Additional temperature sensors are usually installed in parallel to allow for later temperature corrections of the measurements. For such applications, the accuracy of the measurements of MC should be around ±0.5%–2%. Measurement frequencies can

vary approximatively between few minutes to several hours, according to the application and the aim of the monitoring.

The electrodes are usually chrome or stainless steel screws, driven into the wood in predrilled holes, or stainless steel nails. Either insulated or un-insulated needles can be used. Un-insulated electrodes will sense the highest MC along their length; therefore, moisture gradients between the surface and the interior of the cross-section affect the results. The technique is interesting if it is satisfactory to have the MC approximately in the wood 'layer' between two relatively close depths. As structural elements with a large cross-section reach EMC over the whole cross-section in the very long term, it is sometimes preferable to determine the MC as a function of the depth, using electrodes of different lengths, which allows for the assessment of moisture profiles along the cross-section of the structural element. In these cases, electrodes with insulated shanks should be used, measuring MC only at the tip of the electrode. To date, commercial pins allow the measurement at a maximum depth of 7 cm from the surface. A measuring point for the electrical resistance always consists of one pair of pins with a distance of few centimetres between them. The orientation of the pins per pair is perpendicular to the grain, as required by the common resistance method. It has to be outlined that the gap between the electrode and the larger hole has to be seal to avoid that condensed water on the surface could be transported into the wood along the electrodes, giving wrong measurements. The electrodes can be associated with air temperature and relative humidity sensors at the same locations, to allow a comparison between the direct MC measurements and the theoretical EMC based on air temperature and relative humidity data, as for the case of the indirect method.

The physical MC measurement is quite useful not only to analyse the distribution of the MC over the cross-section but also to compare the MC in different positions of the structure. This is particularly interesting when singularity points need to be monitored because of their sensitivity to the presence of water, for example, near supports, at the edges, around connecting steel plates, in exposed structural elements, at the interface between slab and base or flooring and wall. In this sense, some useful monitoring has been performed on timber bridges, trying to improve the maintenance plans and providing economic benefits for owners and minimal disturbance for the users (Fortino *et al.*, 2013; Franke *et al.*, 2013). A 2-year monitoring programme performed on the Obermatt bridge, in Switzerland, has shown that, in general, the MC measured in timber sections follows the seasonal effective climate changes. The MC values at a depth of 200 mm show a smaller seasonal variation than those at the surface (Fig. 7.35A and B). Any difference could not be detected at different longitudinal sections of the bridge, probably because it is too far from the edges and protected against rain or other wet situations. The MC in timber elements subjected to those particular outdoor climate conditions varied between about 12% and 22% during the 1-year monitoring period, which is below the critical MC of about 25% for decay hazards. A well-designed structural protection of the wood against rain or snow to prevent a general penetration of moisture into the timber elements is recommended.

The MC profile with depth is particularly interesting to show the capacity, for wall and flooring timber assemblies, of buffering the indoor climate variations in terms of temperature and humidity. A periodic monitoring has been performed in four occupied

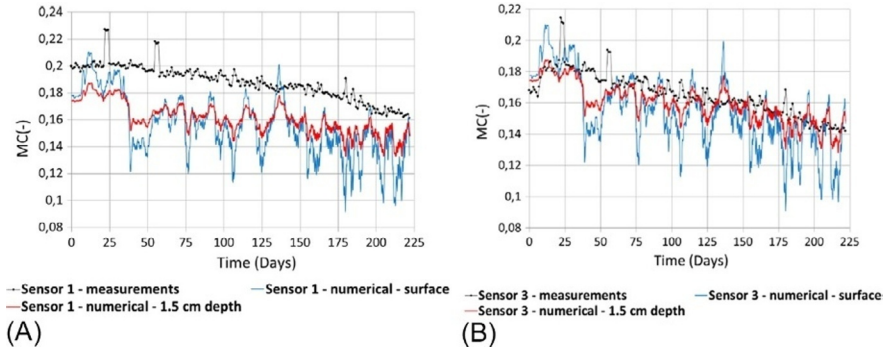


Fig. 7.35 Numerical results and measurements for 222 days for the sensor location at (A) the top of the bridge (values on the surface and at a depth of 1.5 cm) and (B) near the edges of the bridge (values on the surface and at a depth of 1.5 cm) (Fortino *et al.*, 2013).

apartments of a multistorey residential building in Sweden (Hameury and Lundstrom, 2004). Results are affected by the equipment because it was calibrated for a constant temperature and a specific wood species. Nevertheless, qualitative results have shown that a large area of exposed massive wood contributes to buffer the temperature variations, but daily fluctuations in relative humidity have not really been demonstrated.

In addition to these standard methods, neutron imaging (NI) represents an alternative method to determine the MC. Neutrons have a high interaction probability with hydrogen. This allows for a quantitative determination of the moisture distribution within a sample with high spatial resolution.

Near infra-red spectroscopy (NIRS) and optical systems are used for periodic measurements; though at present there are no applications existing to perform a continuous monitoring with these techniques (Sandak *et al.*, 2015).

7.5.3.4 Other types of monitoring

The monitoring methodology should need low maintenance, and monitoring the efficiency of the equipment should be as smooth as possible.

It is recommended to integrate the control of MC and/or of local relative humidity with a mechanical check of deformations of structural elements, considering that both MC gradients and fungal attack would cause an increment of stresses. Thus, the load-bearing capacity of timber elements and systems is affected by MC changes, having an impact on the serviceability and the safety of bio-based materials structures. It is not only fungal attacks that are dangerous, but also termites need special attention through a specific monitoring activity, because they can produce hidden, dangerous decays similar to fungal rot.

7.5.3.5 Mechanical stresses

Nowadays, the most common approach is to use multisensory techniques, that is, a combination of several measuring methods and different sensors, because a single

parameter is generally insufficient to concisely describe the healthy state of a material or of a building to have a service life assessment. In these cases, particular attention has to be given to the choice of the data logger system. Ideally, the same acquisition system should be able to centralise data from different measurements and with different acquisition frequencies. All the available long-term monitoring projects on timber structures show that observed mechanical deformations, such as vertical settlements, longitudinal deformations and long-term creep effects, are strongly influenced by MC gradients induced by climatic variations (shrinking and swelling). It has been observed that the initial deformation after construction is mainly due to drying of timber elements. The following yearly/daily moisture variations give rise to small variations of the deformation. These small deformations follow usually a cyclic trend, according to seasonal variations (Fig. 7.34B). Structural responses for outdoor or indoor elements have been shown to be quite different, in particular, when indirect measurements are taken. This is probably due to the stronger daily variations on the surface that are not representative of the EMC of the whole cross-section. The monitoring system installed in the ESB building, in Nantes (France), shows that for indoor elements, a transient state has appeared at the beginning of the monitoring period, approximatively at the end of the heating period (Fig. 7.36). It seems to be linked with the transition between the initial MC of the elements, estimated at 12% according to European standards, and the current average value of MC, assessed from measurements at around 8% for the indoor elements. Indeed, in the same period, various cracks were listed in the structure, which could be related to a relaxation of moisture induce stresses. After the first year, the behaviour of the indoor elements seems to be periodic, with a yearly period, with some irregularities due to the random variability of the climate year to year (Sorin *et al.*, 2016).

The Limnologen monitoring system is completed by vertical displacement measurements to follow the long-term behaviour of CLT panels for a multistorey building.

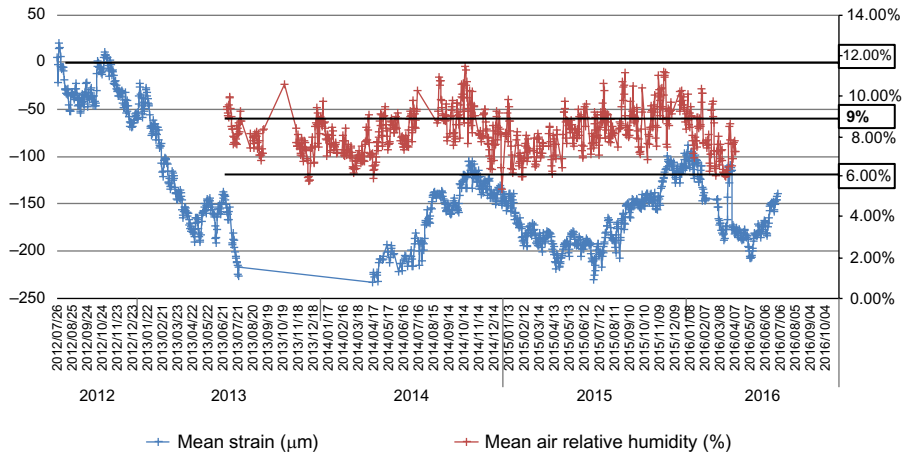


Fig. 7.36 Strain time history for an indoor sensor location and corresponding moisture content (daily mean values) during 4 years of measurements (Lanata, 2015).

After an initial period of about 9 months, during which vertical relative displacement increased monotonically, the total vertical displacement was about 18 mm (Fig. 7.34A and B). This initial strong vertical deformation corresponds to the decreasing of the initial MC, from 18% to 6%, as previously shown. In addition, the displacement varies periodically in annual cycles, with a general trend to increase over time. This is probably related to the creep and the mechanosorptive deformation taking place. It is recommended to start the monitoring period as soon as possible during the construction phase, to be able to measure the instantaneous displacement too.

Dynamic performances have also shown to be dependent on the MC of the measured element. A dynamic monitoring can also be used to detect changes in natural frequencies and modal shapes. This approach has not to be necessarily continuous over time, but periodic dynamic measurements at the same year period, to be not affected by climatic conditions, can be performed and the results compared. The main difference of this approach compared with the previous ones is that the dynamic properties are global parameters; the dynamic monitoring is reliable only if a generalised MC increase is expected and not to detect local moisture accumulations.

Access points should be maintained for on-site monitoring, which should be performed as part of the ordinary maintenance carried out on a regular schedule. In the future, this type of monitoring should be a standard procedure for all buildings made with bio-based materials.

7.5.4 Insect monitoring

If the local hazard due to subterranean termites is present, this should be taken into account during the project of a bio-based building through the adoption of some limiting measures to reduce the risk, such as inspections, physical barriers and preventive treatments of wood and of other bio-based materials.

In Europe, different approaches have been adopted in different countries to hazards from termites. France has, since 1999, adopted obligations of identification of infested areas and notification to the local authorities to treat existing infestations as mandatory and prepurchase inspections during a property sale (Loi n 99-471, 1999). Finally, since 2006, there have been obligations for infested areas that all wood and wood-based products in the building market are made of naturally durable species or treated with appropriate preservatives. Portugal adopted a law only for the Azores, whilst there are no special laws in Italy and a requirement on state of conservation with respect to decay organism in the Building Assessment Report in Spain. Regarding dry-wood insects (e.g. Coleoptera) the hazard is similar across Europe with some specific species that occur only in Southern European countries (e.g. *Trichoferus holosericeus*).

The presence of decay due to insects is visually detected, in some cases with only simple tools (hammer, screwdriver) and in other cases associated with non-destructive (NDT) or micro-destructive techniques such as the resistance drilling method, ultrasound and RF device. The signs of active attacks were evaluated by visual observation of wood surfaces (e.g. bore dust, swarming holes and tunnelling). All these data carried out by direct observation are useful for the diagnosis of attacking species in order to

evaluate the best eradication measures. If necessary, the status of attacks (active or previous) can be detected by electronic acoustic amplifiers. Basically, the device consists of an electronic amplifier coupled with an acoustic transducer and a headphone. A technical integrated approach exists in evaluating insect attacks on on-site timber elements where the assessment is based on different methods, that is, visual inspection and acoustic detection (Feci *et al.*, 2013). Acoustic devices are useful for the detection *in situ* but are unable to be used as a permanent monitoring system due to the interferences of human activities and other external noises. Although there are no examples in the literature, overnight monitoring could prove effective. Some trials on new methods for monitoring insect decay on buildings are described in literature. A device based on light emission and recapture of reflexion coupled with moisture-temperature sensor that sends an alarm was described but at the moment no real application is known (Oliver Villanueva and Albian-Perez, 2013). The alarm is given when the insect appears within wood or when the conditions in wood make it vulnerable to fungi settlement.

The early detection of insect attacks in service is difficult to detect due to the fact that the first visible signs, e.g. swarming, holes, adults, etc., occur after the beginning of an infestation when the wood mechanical properties may have already been compromised (e.g. termite attacks). So, if the continuous monitoring of wood moisture or environmental humidity can help in warning about the possibility of occurring an insect attack (especially termites that need high humidity also if they can obtain the right moisture level to survive from wall or ground), only visual periodic inspection can detect the movement of termites. Visual inspections can be associated with different NDT techniques like thermal imaging based on heat emission from the insect body, gas sensors that detect the gas production by termites and microwave technology. Most of these methods are commercialised and already reported in the literature (Fujii, 2001; Fujii and Yanase, 2001; Miura *et al.*, 2014; Fujii *et al.*, 2007). Whilst for fungal attack the elected parameter of analysis is still the wood MC, in the case of insects, different methods can help identify an active attack before there is evidence on the wood surface. When the wooden structure is hidden, as for CLT panels, to date, no solutions are described in literature. Anyway, this type of building product has a very low risk of coleopteran decay, due to the high temperature reached during manufacture that kills the insect within the panel and to the fact that during the in-service condition it cannot be reached by a hypothetical swarming adult from other infested wood. In fact, only the panel storage after production and the construction site storage prior to installation could represent a risk for an infestation by Coleoptera or dry wood termites.

In the case of termites, food is foraged by workers from the nearby surroundings and transported back to the nest. In this case, if any preservative treatment is applied on wood, only a periodical survey can limit the possibility of attack. Chemical and physical barriers in the soil around the wooden building represent a control measure to protect the site. A more environmental friendly method than insecticides is the installing of perimeter bait stations for controlling termite activity around the building area. Several companies commercialise the baits; their mechanisms can be described in the followings steps. In a first phase, pieces of non-toxic food (e.g. wood or cellulosic matrix) are put into the station installed in the soil around the inspected

building. When termites are noticed, a slow-acting toxicant (generally anti-moult molecules) bait is added to food inside the stations. The slow action allows the feeding termites to return to the colony and infect the entire colony. The non-toxic baits in the station could be placed for the entire service life of a building or for a periodical monitoring. This method is expensive and a rapid early screening method could be utilised during the other monitoring periods mandatory for each new built timber structure.

7.5.5 In-service testing

The in-service testing has the aim of evaluating the efficiency of the timber structure through non-destructive tools. The basic consideration is that the simple passage of time does not cause a decay of the mechanical performance of wood, except the well-known creep phenomenon easily configurable through the available, published tables (CEN, 2004).

From this consideration, any changes in the structure performance are due to biological degradations, caused by insect or fungal attack, or by structural degradations caused by overload situations that may have triggered cracks or disconnections.

Any in-service testing needs a complete access to the timber structure, to evaluate the following:

- Structure type: hierarchical frame structure and box-framed structure
- Wood material: massive, glulam, other structural panels and wood species
- Original characteristics of the material: the presence and nature of defects, glue, etc.
- Variations occurred during the use of the structure: biological attacks and structural damages

The international standard ISO 13822:2001 (ISO, 2010) has the ultimate goal to limit construction intervention to a strict minimum, a goal that is clearly in agreement with the principles of sustainable development. To accomplish that, it provides general requirements and procedures for the assessment of existing structures (buildings, bridges, industrial structures, etc.) based on the principles of structural reliability and consequences of failure. The standard is applicable to the assessment of any type of existing structure, of any material.

Even if only partially applicable, at least the aims are similar and the schemes suggested within the standard can be considered a useful framework for the on-site inspection of a bio-based building.

The Italian standard UNI 11119 (UNI, 2004), on the other side, is devoted to the on-site inspection of historic timber structures.

Both standards cover aspects that in part are overlapping the aim of the inspection analysed in our chapter. Combining the two, that share a similar approach, it will be possible to establish guidelines for the on-site inspection of existing bio-based building materials.

7.5.5.1 Visual inspection

Independently from the structure typology and from the material, any service testing will need a preliminary visual inspection. The typical timber structures are of hierarchical type: a principal structure supporting members of lower hierarchical level, generally also smaller in section and length. Not only are the most frequent made of solid timber,

but also glulam structures follow similar schemes. Generally, the different levels of timber structures are almost completely visible. Modern CLT structures are box-framed and hidden: all the elements composing walls and floors are structurally of the same principal importance, and generally, they are hidden by fire-proofed panels.

Independently from all the factors, on-site tests need timber members completely uncovered/uncoated to evaluate wood species; wood typology; presence, nature and dimensions of defects; and traces of possible biological and physical damages. Briefly, the visual inspection aims are the estimation of the original characteristics of any wood member and an evaluation of the effects of time and use (Cruz *et al.*, 2015).

The original characteristics of massive timber structures are principally given by wood species and defect features, whilst on structural panels the original characteristics are declared by the producer and principally affected by the characteristic and efficacy of glues and gluing methodology.

Wood identification is crucial for a correct evaluation of mechanical characteristics of timber members; thus, the result should be as reliable as possible. If any incertitude from an identification via direct visual observation exists, a sample should be drawn and identified through anatomical observations by a specialist.

Visual strength grading (*VSG*) is known to be the most performed and reliable methodology used to evaluate on-site the structural performances of a timber member (Sousa *et al.*, 2013; Feio and Machado, 2015). VSG is still the most suitable method for the preliminary survey, being able to deliver – if properly used – conservative information about the reference properties of the various timber members. The Italian standard UNI 11119 (UNI, 2004) was one of the first standards presenting a specific visual grading methodology for in situ appraisal of the quality of structural timber members, and it is currently recognised as the leading approach in Europe. Some papers describe possible improvements of the traditional VSG for sawmills in order to have a better tool for on-site VSG (Anthony *et al.*, 2009; Anthony, 2013). Several papers describe non-destructive or low-destructive methodologies to enhance the results obtained from VSG in order to better estimate the real strength of each member (e.g. Piazza and Riggio, 2008; Kasal, 2010; Kasal and Tannert, 2011; Cavalli and Togni, 2013; Sousa *et al.*, 2013; Feio and Machado, 2015). Most applied are local density, through hardness or screw extraction, and ultrasound measurements (Sousa *et al.*, 2013; Machado, 2013), but some other more impacting test are considered, such as density or mechanical characterisation of cores extracted from the members. The VSG is not applicable, as already stated, to both glulam and other engineered wood elements, such as CLT. In any case, a visual inspection is compulsory, because it will allow observation of other clues that are important to evaluate the possible presence of different decay typologies.

7.5.5.2 Decay inspection

Only the complete access and the visual inspection with the help of NDT instruments can detect early biotic decay.

The surface traces of presence of moisture must be considered an alarm for a possible presence of hidden fungal decay due to the entry of water within the interstices, where it may remain and allow fungal attack.

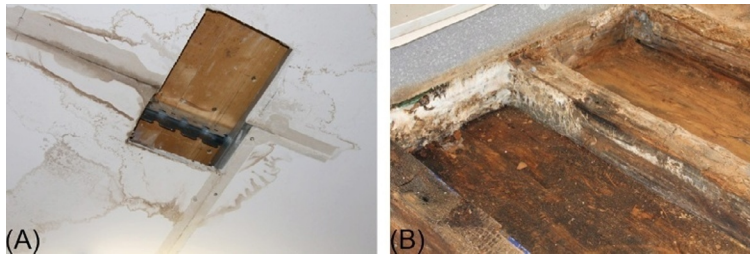


Fig. 7.37 (A) A frame cut near the signs of moisture on plasterboard for measuring the wood MC and (B) fungal decay hidden by the plasterboard.
Courtesy of IVALSA.

When the timber structure is not visible, such as for CLT panels, the only possibility of detection remains the moisture traces on the plasterboard covering the timber structure, but often these signs can only indicate the presence of an already severe decay problem. This highlights the importance of monitoring in buildings of this type. Indeed, the in-service testing example presented in Fig. 7.37A and B indicated that the surface traces on the plasterboard not only allowed an early detection, but revealed a severe fungal decay, capable of causing a collapse (after only 2 years of service life).

Typically, insect holes are not only clues but also evidence of insect attack. Generally speaking, they involve only the surface of the element; though this is not the case for termite attack, which is invasive and dangerous in a way similar to the fungal rots.

There are several non-destructive or low-destructive tools to evaluate the incidence of biotic decay. The aim of their use is the measurement of the extent of the decay in order to have a reliable measurement of the real collaborating section.

A first very simple tool is the hammer: hammering on a solid wood element with an internal, hidden attack by fungal decay returns a duller sound than the sound wood. This is not a way to measure the presence of decay, but experience will allow finding the decayed portion, where a more precise tool can be applied to have a reliable and useful result.

7.5.5.3 Instrumented survey

Where wood MC measurements and other traces indicate the possible presence of internal fungal rot decay, the tool currently considered the most reliable is the drilling resistance (Rinn, 2012; Rinn, 2013), at present considered as a reference method (Beni *et al.*, 2015).

On solid wood, the drilling resistance method allows detecting and measuring the decayed portions of both the surface decay, for example, from Coleoptera, and the inner decay, not directly, visually detectable (Nowak *et al.*, 2016) as in Fig. 7.38. Drilling resistance method is at present the only method useful to detect the presence of decay in the member's portion inserted into walls. This is a method that cannot be considered as a destructive one, even if low-invasive.

Ultrasound velocity is largely used perpendicularly to the grain, as a tomographic tool and sound velocity in the same direction. Through the tomographic methodology,

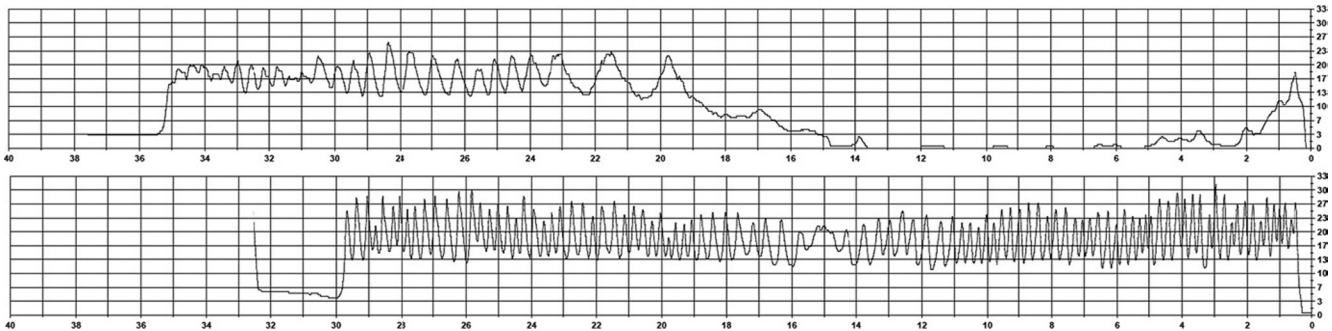


Fig. 7.38 *Above*, a drilling profile on a partially (on the right) decayed member. *Below*, a sound member of the same species (European fir). Both profiles are made at IVALSA.

by means of multiple measurements, the identifiable dimensions of the decayed section can be reliably determined. The problem that needs be solved is the contact between wood and sensors, which is not easy in the case of degraded wood member surface.

Whilst wood coring to evaluate the presence and estimate the dimensions of the decayed section is too invasive, particularly when the coring is made by means of an electric drilling machine driving a going head milling borer, an interesting and promising but not invasive method seems to be the microwave reflectometer (*MWR*), described in Beni *et al.* (2015), even if still at a laboratory stage.

7.5.6 Summary of monitoring methods

With the aim to lengthen the useful life of the buildings, the monitoring of bio-based buildings should be an integral part of the building project. In particular, it is of fundamental importance for those buildings in which the structural elements are always hidden by different types of panels, with a particular mention of the fire-resistant.

The activity of in-service testing is complementary to the monitoring. Whilst the latter allows to check the overall state of the structure, in case of alerts, the in-service testing verifies risk situations to determine their causes and to evaluate the consequences.

References

Adan, O.C.G., 1994. On the Fungal Defacement of Interior Finishes (Ph.D. Thesis). Eindhoven University of Technology, Eiendhoven.

Alfredsen, G., Larnøy, E., 2006. Dynamic MOE testing of wood: the influence of wood protecting agents and moisture content on ultrasonic pulse and resonant vibration. Wood Res. 51 (1), 11–20.

Altgen, M., Militz, H., 2016. Influence of process conditions on hygroscopicity and mechanical properties of European beech thermally modified in a high-pressure reactor system. Holzforschung. http://dx.doi.org/10.1515/hf-2015-0235.

Anthony, R.W., 2013. Development and understanding for grading timber in existing buildings. Adv. Mater. Res. 778, 1049–1055.

Anthony, R.W., Dugan, K.D., Anthony, D.J., 2009. A grading protocol for structural lumber and timber in historic structures. APT Bull. J. Preserv. Technol. XL-2-09, 3–9.

Araujo, C.D., MacKay, A.L., Whittal, K.P., Hailey, J.R.T., 1993. A diffusion model for spin-spin relaxation of compartmentalized water on wood. J. Magn. Reson. B 101, 248–261.

ASTM, 1999. ASTM D1413-99:1999. Standard Test Method for Wood Preservatives by Laboratory Soil-Block Cultures. ASTM International, West Conshohocken, PA.

ASTM, 2010. ASTM D5590:2010. Determining the Resistance of Paint Films and Related Coatings to Fungal Defacement by Accelerated Four-Week Agar Plate Assay. ASTM International, West Conshohocken, PA.

ASTM, 2011a. ASTM D3273:2011. Standard Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber. ASTM International, West Conshohocken, PA.

ASTM, 2011b. ASTM D3345:2011. Standard Test Method for Laboratory Evaluation of Wood and Other Cellulosic Materials for Resistance to Termites, ASTM International, West Conshohocken, PA.

ASTM, 2015. ASTM D4445:2015. Standard Test Method for Fungicides for Controlling Sapstain and Mold on Unseasoned Lumber (Laboratory Method). ASTM International, West Conshohocken, PA.

ASTM, 2016. ASTM D2574:2016. Standard Test Method for Resistance of Emulsion Paints in the Container to Attack by Micro-organisms. ASTM International, West Conshohocken, PA.

AWPA, 1998. AWPA E11-97:1998. Standard Method for Determining the Leachability of Wood Preservatives. American Wood Protection Association.

AWPA, 2013a. AWPA E7:2013. Standard Field Test for Evaluation of Wood Preservatives to be Used in Ground Contact (UC4A, UC4B, UC4C), Stake Test. American Wood Protection Association.

AWPA, 2013b. AWPA E9:2013. Standard Field Test for the Evaluation of Wood Preservatives to be Used Above Ground (UC3A and UC3B): L-Joint Test. American Wood Protection Association.

AWPA, 2013c. AWPA E16:2013. Standard Field Test for Evaluation of Wood Preservatives to be Used Above Ground (UC3B): Horizontal Lap-Joint Test. American Wood Protection Association.

AWPA, 2013d. AWPA E18:2013. Standard Field Test for Evaluation of Wood Preservatives to be Used Above Ground (UC3B), Ground Proximity Decay Test. American Wood Protection Association.

AWPA, 2013e. AWPA E25:2013. Standard Field Test for Evaluation of Wood Preservatives to be Used Above Ground (UC3B): Decking Test. American Wood Protection Association.

AWPA, 2013f. AWPA E27:2013. Standard Field Test for Evaluation of Wood Preservatives to be Used Above Ground (UC3B): Accelerated Horizontal Lap Joint Test. American Wood Protection Association.

AWPA, 2015a. AWPA E21:2015. Standard Field Test Method for the Evaluation of Wood Preservatives to be Used for Interior Applications (UC1 and UC2); Full-size Commodity Termite Test. American Wood Protection Association.

AWPA, 2015b. AWPA E26:2015. Standard Field Test for Evaluation of Wood Preservatives Intended for Interior Applications (UC1 and UC2): Ground Proximity Termite Test. American Wood Protection Association.

AWPA, 2016. AWPA E1:2016. Laboratory Methods for Evaluating the Termite Resistance of Wood-based Materials: Choice and No-choice Tests. American Wood Protection Association.

AWPC, 2015. Protocols for Assessment of Wood Preservatives. Australian Wood Preservation Committee, Ensis, Clayton.

Ayerst, G., 1969. Effects of moisture and temperature on growth and spore germination in some fungi. J. Stored Prod. Res. 5, 127–141.

Back, E.L., Salmén, N.L., 1982. Glass transitions of wood components hold implications for molding and processing. Tappi J. 65, 107–110.

Bahmani, M., Fromm, J., Schmidt, O., Melcher, E., 2015a. Residual metal content and metal distribution in chromium/copper-treated wood after field and laboratory leaching exposure. Eur. J. Wood Wood Prod. 73, 377–384.

Bahmani, M., Fromm, J., Schmidt, O., Melcher, E., 2015b. Influence of exposure time, wood species and dimension on the remaining copper and chromium content in CC-treated wood after field and laboratory leaching tests. Holzforschung 69 (9), 1143–1150.

Barnacle, J.E., Cookson, L.H., 1990. Treated eucalypt and pine sapwood after 25 years in the sea. Part 1. Major effect of wood type on the efficacy of certain creosotes against *Limnoria tripunctata* Menzies. J. Inst. Wood Sci. 11, 213–220.

Becker, G., 1955. Über die Giftwirkung von anorganischedn Salzen, alpha-Chlornaphthalin und Kontaktinsektiziden auf die Holzbohrassel *Limnoria*. Holz Roh Werkst. 13, 457–461.

Behr, E.A., 1972. Decay and termite resistance of medium density fibreboard made from wood residue. For. Prod. J. 22 (12), 48–51.

Beni, S., Macchioni, N., Mannucci, M., Olmi, R., Palanti, S., Riminesi, C., 2015. First trials for a microwave reflectometric tool to survey decay in historic timber structures. Int. J. Archit. Herit. 9 (6), 665–673.

Berthold, J., Rinaudo, M., Salmén, L., 1996. Association of water to polar groups – estimations by an adsorption model for ligno-cellulosic materials. Colloids Surf. A112, 117–129.

Birkinshaw, C., McCarthy, C.J., Regan, N., Hale, M.D.C., Cahill, D., McCourt, M., 1999. The thermomechanical behaviour of wood subject to fungal decay. Holzforschung 53, 459–464.

Björdal, C.G., 2012. Evaluation of microbial degradation of shipwrecks in the Baltic Sea. Int. Biodeter. Biodegr. 70, 126–140.

Blom, A., Bergstrom, M., 2005. Mycologg: a new accelerated test method for wood durability above ground. Wood Sci. Technol. 39, 663–673.

Borges, L.M.S., Cragg, S.M., Bergot, J., Williams, J.R., Shayler, B., Sawyer, G.S., 2008. Laboratory screening of tropical hardwoods for natural resistance to the marine borer *Limnoria quadripunctata*: the role of leachable and non-leachable factors. Holzforschung 62, 99–111.

Borges, L.M.S., Cragg, S.M., Busch, S., 2009. A laboratory assay for measuring feeding and mortality of the marine wood borer Limnoria under forced feeding conditions: a basis for a standard test method. Int. Biodeter. Biodegr. 63, 289–296.

Borges, L.M.S., Merckelbach, L.M., Cragg, S.M., 2014. Biogeography of wood-boring crustaceans (Isopoda: Limnoriidae) established in European coastal waters. PLoS One 9 (10).

Bravery, A.F., 1979. A miniaturised wood-block test for the rapid evaluation of wood preservative fungicides. Rep. No. 136. Swedish Wood Preservation Institute, Stockholm, pp. 58–65.

Bravery, A., Lea, R., 1987. Assessing the fungus resistance of wood based composites. In: Protection of Wood Based Composite Products 1987. Proc. IUFRO Symposium on Protection of Wood Based Composite Products, pp. 67–86.

Breslin, V.T., Adler-Ivanbrook, L., 1998. Release of copper, chromium and arsenic from CCA-C treated lumber in estuaries. Estuar. Coast. Shelf Sci. 46, 111–125.

Brischke, C., Lampen, S.C., 2014. Resistance based moisture content measurements on native, modified, and preservative treated wood. Eur. J. Wood Wood Prod. 72, 289–292.

Brischke, C., Rapp, O.A., Bayerbach, R., 2006. Decay influencing factors: a basis for service life prediction of wood and wood based products. Wood Mater. Sci. Eng. 1, 91–107.

Brischke, C., Rapp, A.O., Bayerbach, R., 2008a. Measurement system for long-term recording of wood moisture content with internal conductively glued electrodes. Build. Environ. 43, 1566–1574.

Brischke, C., Rapp, A.O., Bayerbach, R., Morsing, N., Fynholm, P., Welzbacher, C.R., 2008b. Monitoring the "material climate" of wood to predict the potential for decay: results from in situ measurements on buildings. Build. Environ. 43, 1575–1582.

Brischke, C., Meyer, L., Olberding, S., 2014. Durability of wood exposed in ground – comparative field trials with different soil substrates. Int. Biodeterior. Biodegrad. 86, 108–114.

Brooks, K.M., 2001. The Environmental Risks Associated With the Use of Pressure Treated Wood in Railway Rights-of-Way. 8 pp. http:/www.rta.org/assets/docs/RTASponsoredResearch/Environmental/environmental risks associated with pressure treated wood.pdf.

BS, 1990. BS 1982:1990 Part 1. Method for Determining Resistance of Wood to Wood Rotting Basidiomycetes. British Standards Institution, London.

BS, 1989. BS 3900-G6:1989. Methods of Test for Paints. Assessment of Resistance to Fungal Growth. British Standards Institution, London.

Burkhardt, M., Kupper, T., Hean, S., Haag, R., Schmid, P., Kohler, M., Boller, M., 2007. Biocides used in building materials and their leaching behaviour to sewer systems. Water Sci. Technol. 56 (12), 63–67.

Burud, I., Gobakken, L.R., Fløa, A., Kvaal, K., Thiis, T.K., 2015. Hyperspectral imaging of blue stain fungi on coated and uncoated wooden surfaces. Int. Biodeterior. Biodegrad. 88, 37–43.

CABI, 2011. *Limnoria quadripunctata* [original text by S. M. Cragg]. Invasive Species Compendium. CAB International, Wallingford.

Cavalli, A., Togni, M., 2013. How to improve the on-site MOE assessment of old timber beams combining NDT and visual strength grading. Nondestr. Test. Eval. 28, 252–262.

CEN, 1974. EN 22:1974. Wood Preservatives. Determination of Eradicant Action Against *Hylotrupes bajulus* (Linnaeus) Larvae (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 1988. EN 21:1988. Wood Preservatives. Determination of the Toxic Values Against *Anobium punctatum* (De Geer) by Larval Transfer (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 1992a. EN 20-1:1992. Wood Preservatives. Determination of the Protective Effectiveness Against *Lyctus brunneus* (Stephens). Application by Surface Treatment (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 1992b. EN 275:1992. Wood Preservatives – Determination of the Protective Effectiveness Against Marine Borers. European Committee for Standardization, Brussels, Belgium.

CEN, 1993a. EN 20-2:1993. Wood Preservatives. Determination of the Protective Effectiveness Against *Lyctus brunneus* (Stephens). Application by Impregnation (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 1993b. EN 370:1993. Wood Preservatives. Determination of Eradicant Efficacy in Preventing Emergence of *Anobium punctatum* (De Geer). European Committee for Standardization, Brussels, Belgium.

CEN, 1996. EN 113:1996. Wood Preservatives – Test Method for Determining the Protective Effectiveness Against Wood Destroying Basidiomycetes – Determination of the Toxic Values. European Committee for Standardization, Brussels, Belgium.

CEN, 1997a. EN 84:1997. Wood Preservatives – Accelerated Ageing of Treated Wood Prior to Biological Testing – Leaching. European Committee for Standardization, Brussels, Belgium.

CEN, 1997b. EN ISO 846:1997. Plastics: Evaluation of the Action of Microorganisms. European Committee for Standardization, Brussels, Belgium.

CEN, 2002a. EN 13183-1:2002. Moisture Content of a Piece of Sawn Timber – Part 1: Determination by Oven-Dry Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2002b. EN 13183-2:2002. Moisture Content of a Piece of Sawn Timber – Part 2: Estimation by Electrical Resistance Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2003. EN/TS 12037:2003. Wood Preservatives – Field Test Method for Determining the Relative Protective Effectiveness of a Wood Preservative Exposed Out of Ground Contact – Horizontal Lap-Joint Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2004. EN 1995:2004. Eurocode 5: Design of Timber Structures. European Committee for Standardization, Brussels, Belgium.

CEN, 2005a. EN 48:2005. Wood Preservatives. Determination of Eradicant Action Against Larvae of *Anobium punctatum* (De Geer) (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2005b. EN 13183-3:2005. Moisture Content of a Piece of Sawn Timber Part 3. Determination by Capacitance Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2005c. EN/TS 15083-1:2005. Durability of Wood And Wood-Based Products – Determination of the Natural Durability of Solid Wood Against Wood-Destroying Fungi. Test Methods – Part 1: Basidiomycetes. European Committee for Standardization, Brussels, Belgium.

CEN, 2005d. EN/TS 15083-2:2005. Durability of Wood And Wood-Based Products – Determination of the Natural Durability of Solid Wood Against Wood-Destroying Fungi. Test Methods – Part 2: Soft Rotting Micro-Fungi. European Committee for Standardization, Brussels, Belgium.

CEN, 2006a. EN 335-1:2006. Durability of wood and wood-based products. Definitions of use classes. General. European Committee for Standardization, Brussels, Belgium.

CEN, 2006b. EN/TS 927-5:2006. Paints and Varnishes. Coating Materials and Coating Systems for Exterior Wood. Assessment of the Liquid Water Permeability. European Committee for Standardization, Brussels, Belgium.

CEN, 2006c. EN 1390:2006. Wood Preservatives. Determination of the Eradicant Action Against *Hylotrupes bajulus* (Linnaeus) Larvae. Laboratory Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2008. EN/TS 15119-1:2008. Durability of Wood and Wood-Based Products, Determination of Emissions from Preservative Treated Wood to the Environment Part 1: Wood held in the storage yard after treatment and wooden commodities in Use Class 3 (Not Covered, Not in Contact With the Ground) – Laboratory Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2011. EN 152:2011. Wood Preservatives. Determination of the Protective Effectiveness of a Preservative Treatment Against Blue Stain in Wood in Service. European Committee for Standardization, Brussels, Belgium.

CEN, 2012a. EN 117:2012. Wood Preservatives. Determination of Toxic Values Against *Reticulitermes* Species (European Termites) (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2012b. EN 927-3:2012. Paints and Varnishes – Coating Materials and Coating Systems for Exterior Wood – Part 3: Natural Weathering Test. European Committee for Standardization, Brussels, Belgium.

CEN, 2012c. EN/TS 15119-2:2012. Durability of Wood and Wood-Based Products, Determination of Emissions from Preservative Treated Wood to the Environment – Part 2: Wooden Commodities Exposed in Use Class 4 or 5 (In Contact With the Ground, Fresh Water or Sea Water) – Laboratory Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2013a. EN 118:2013. Wood Preservatives. Determination of Preventive Action Against Reticulitermes Species (European Termites) (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2013b. EN 335:2013. Durability of Wood and Wood-Based Products. Uses Class: Definitions, Application to Solid Wood and Wood-Based Products. European Committee for Standardization, Brussels, Belgium.

CEN, 2013c. prEN/TS 16637-2:2013. Construction Products – Assessment of Release of Dangerous Substances – Part 2: Horizontal Dynamic Surface Leaching Test. European Committee for Standardization, Brussels, Belgium.

CEN, 2014a. EN 73:2014. Wood Preservatives – Accelerated Ageing of Treated Wood Prior to Biological Testing – Evaporative Ageing Procedure. European Committee for Standardization, Brussels, Belgium.

CEN, 2014b. EN 252:2014. Durability of Wood and Wood-Based Products. Field Test Method for Determining the Relative Protective Effectiveness of a Wood Preservative in Ground Contact. European Committee for Standardization, Brussels, Belgium.

CEN, 2014c. EN 330:2014. Wood Preservatives – Determination of the Relative Protective Effectiveness of a Wood Preservative for Use Under a Coating and Exposed Out-of-Ground Contact – Field Test: L-Joint Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2014d. EN 15457:2014. Paints and varnishes. Laboratory Method for Testing the Efficacy of Film Preservatives in a Coating Against Fungi. European Committee for Standardization, Brussels, Belgium.

CEN, 2014e. EN 16492:2014. Paints and Varnishes – Evaluation of the Surface Disfigurement Caused by Fungi and Algae on Coatings. European Committee for Standardization, Brussels, Belgium.

CEN, 2014f. EN/TR 16663:2014. Durability of Wood and Wood-Based Products – Determination of Emissions From Preservative Treated Wood to the Environment – Wooden Commodities Exposed in Use Class 3 (Not Covered, Not in Contact With the Ground) – Semi-Field Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2015a. EN 49-2:2015. Wood Preservatives. Determination of the Protective Effectiveness Against Anobium punctatum (De Geer) by Egg-Laying and Larval Survival. Application by Impregnation (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2015b. prEN 16818:2015. Moisture Dynamics of Wood and Wood-Based Products. European Committee for Standardization, Brussels, Belgium.

CEN, 2016a. EN 46-1:2016. Wood Preservatives. Determination of the Preventive Action Against Recently Hatched Larvae of Hylotrupes bajulus (Linnaeus). Application by Surface Treatment (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2016b. EN 46-2:2016. Wood Preservatives. Determination of the Preventive Action Against Recently Hatched Larvae of Hylotrupes bajulus (Linnaeus). Ovicidal Effect (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2016c. EN 47:2016. Wood Preservatives. Determination of the Toxic Values Against Larvae of Hylotrupes bajulus (Linnaeus) (Laboratory Method). European Committee for Standardization, Brussels, Belgium.

CEN, 2016d. EN 49–1:2016. Wood Preservatives. Determination of the Protective Effectiveness Against Anobium punctatum (De Geer) by Egg-Laying and Larval Survival. Application by Surf. European Committee for Standardization, Brussels, Belgium.

CEN, 2016e. EN 350:2016. Durability of Wood and Wood-Based Products. Testing and Classification of the Durability to Biological Agents of Wood and Wood-Based Materials. European Committee for Standardization, Brussels, Belgium.

Chang, S.J., Olson, J.R., Wang, P.C., 1989. NMR imaging of internal features in wood. For. Prod. J. 39, 43–49.

Chaudhry, G.R., Chapalamadugu, S., 1991. Biodegradation of halogenated organic compounds. Microbiol. Rev. 55 (1), 59–79.

Chen, J.P., Wu, S., 2004. Simultaneous adsorption of copper ions and humic acid onto an activated carbon. J. Colloid Interface Sci. 280, 334–342.

Chirkova, J., Andersone, I., Grinins, J., Andersons, B., 2013. Sorption properties of hydrothermally modified wood and data evaluation based on the concept of Hansen solubility parameter (HSP). Holzforschung 67, 595–600.

Christensen, G.N., Kelsey, K.E., 1959. Die Geschwindigkeit der Wasserdampfsorption durch Holz. Holz Roh Werkst. 17, 178–188.

Clausen, C.A., 1996. Bacterial associations with decaying wood: a review. Int. Biodeter. Biodegr. 37 (1–2), 101–107.

Clausen, C.A., Kartal, S.N., 2003. Accelerated detection of brown-rot decay: comparison of soil block test, chemical analysis, mechanical properties and immunodetection. For. Prod. J. 53 (11–12), 90–94.

Clausen, C.A., Green III, F., Highley, T.L., 1991. Early detection of brown-rot decay in southern yellow pine using immunodiagnostic procedures. Wood Sci. Technol. 26 (1), 8.

Clément, J.L., Bagnères, A.G., Uva, P., Wilfert, L., Quintana, A., Reinhard, J., Dronnet, S., 2001. Biosystematics of reticulitermes termites in Europe: morphological, chemical and molecular data. Insect. Soc. 48, 202–215.

Cockcroft, R., 1973. Glue line additives for protecting plywood. International Research Group for Wood Preservation Document, IRG/WP/2102.

Cockroft, R., Laidlaw, R.A., 1978. Factors affecting leaching of preservatives in practice. In: Proceedings IRG Annual Meeting: IRG/WP 78-3113.

Coleman, C.O., Renz, A., 2009. Cheluridae. Zootaxa 2260, 339–343.

Cookson, L.J., 1991. Australasian species of Limnoriidae (Crustacea: Isopoda). Mem. Mus. Victoria 52, 137–262.

Cookson, L.J., Woods, T.L., 1995. Laboratory method used to test the effectiveness of chlorothalonil against marine borers. Wood Prot. 3, 9–15.

Cooper, P.A., 1991. Leaching of CCA from treated wood: pH effects. For. Prod. J. 41, 30–32.

Cooper, P.A., Jeremic, D., Taylor, J.L., Ung, Y.T., Kazi, F., 2001. Effect of humic acid on leaching of CCA from treated wood. For. Prod. J. 51 (9), 73–77.

Cragg, S.M., 1988. The wood-boring isopod Sphaeroma a threat to maritime structures in warm waters. In: Houghton, D.R., Smith, R.N., Eggins, H.O.W. (Eds.), Biodeterioration Book, vol. 7. Elsevier, London.

Cragg, S.M., 2003. Marine wood boring arthropods: ecology, functional anatomy and control measures. In: Goodell, B., Nicholas, D.D., Schultz, T.P. (Eds.), Wood Deterioration and Preservation: Advances in our Changing World. American Chemical Society. Oxford University Press, Oxford.

Cragg, S.M., Danjon, C., Mansfield-Williams, H., 2007. Contribution of hardness to the natural resistance of a range of wood species to attack by the marine borer Limnoria. Holzforschung 61, 201–206.

Cragg, S.M., Beckham, G.T., Bruce, N.C., Bugg, T.D.H., Distel, D.L., Dupree, P., Etxabe, A.G., Goodell, B.S., Jellison, J., McGeehan, J.E., McQueen-Mason, S.J., Schnorr, K., Walton, P.H., Watts, J.E.M., Zimmer, M., 2015. Lignocellulose degradation mechanisms across the Tree of Life. Curr. Opin. Chem. Biol. 29, 108–119.

Creffield, J.W., 1994. A field method for determining the above ground resistance of wood and wood products to attack by subterranean termites. In: The International Research Group on Wood Protection, IRG/WP 94-20035.

Cruz, H., Yeomans, D., Tsakanika, E., Macchioni, N., Jorissen, A., Touza, M., Mannucci, M., Lourenço, P.B., 2015. Guidelines for the on-site assessment of historic timber structures. Int. J. Archit. Herit. 9, 277–289.

CSTB, 2012. Documents Governing the Technical Assessment and Technical Application Document Procedure. CSTB, Marne-la-vallée.

Curling, S., Murphy, R., 1999. The effect of artificial ageing on the durability of wood based board materials against basidiomycete decay fungi. Wood Sci. Technol. 33 (4), 245–257.

Curling, S., Clausen, C.A., Winandy, J.E., 2002a. Experimental method to quantify progressive stages of decay of wood by basidiomycete fungi. Int. Biodeterior. Biodegrad. 49 (1), 13–19.

Curling, S., Clausen, C.A., Winandy, J.E., 2002b. Relationships between mechanical properties, weight loss and chemical composition of wood during incipient brown rot decay. For. Prod. J. 52 (7–8), 34–39.

Curling, S.F., Stefanowski, B.K., Mansour, E., Ormondroyd, G.A., 2015. Applicability of wood durability testing methods to bio-based building materials. In: International Research Group on Wood Preservation Document, IRG/WP/15-20561.

Cymorek, S., 1977. Test methods for wood preservatives against Lyctus: (1) Testing of treated veneer. (2) Testing of glue-line treated plywood (laboratory methods). In: The International Research Group on Wood Protection, IRG/WP 293.

Dealteris, J.T., Bullock, R.C., Romey, W.R., 1988. Alternative treatments to prevent the biodeterioration of offshore wood lobster traps by the wood-boring bivalve *Xylophaga atlantica*. J. Shellfish Res. 7, 445–451.

Delgery, C.C., Cragg, S.M., Busch, S., Morgan, E.A., 2006. Effects of the epibiotic heterotrich ciliate *Mirofolliculina limnoriae* and of moulting on faecal pellet production by the wood-boring isopods, *Limnoria tripunctata* and *Limnoria quadripunctata*. J. Exp. Mar. Biol. Ecol. 334, 165–173.

Deppe, H.J., 1987. Protection of wood based panels against decay and fire – actual situation in the EC and further development. In: Proceedings of the I.U.F.R.O. Wood Protection Subject Group 1987, pp. 145–166.

Deppe, H.J., Gersonde, M., 1977. Technological advances in the production and testing of preserved wood based panel products. J. Inst. Wood Sci. 5, 20–25.

DIN, 1972. DIN 52172-2:1972. Testing of Wood Preservatives; Accelerated Ageing of Preserved Wood, Strain by Washing Out for the Determination of the Quantity of Effective Substance. Deutsches Institut für Normung e. V. (German Institute for Standardization), Berlin, Germany.

Dinwoodie, J.M., 1978. The properties and performance of particle board adhesives. J. Inst. Wood Sci. 8 (2), 59–68.

Distel, D.L., Amin, M., Burgoyne, A., Linton, E., Mamangkey, G., Morrill, W., Nove, J., Wood, N., Yang, J., 2011. Molecular phylogeny of Pholadoidea Lamarck, 1809 supports a single origin for xylotrophy (wood feeding) and xylotrophic bacterial endosymbiosis in Bivalvia. Mol. Phylogenet. Evol. 61, 245–254.

Dubey, S.K., Roy, U., 2003. Biodegradation of tributyltins (organotins) by marine bacteria. Appl. Organomet. Chem. 17, 3–8 (Review).

Dvinskikh, S.V., Henriksson, M., Berglund, L.A., Furó, I., 2011. A multinuclear magnetic resonance imaging (MRI) study of wood with absorbed water: estimating bound water concentration and local wood density. Holzforschung 65, 103–107.

Eaton, R.A., Cragg, S.M., 1995. Evaluation of creosote fortified with synthetic pyrethroids as wood preservatives for use in the sea.1. Efficacy against marine wood-boring molluscs and crustaceans. Mater. Org. 29, 211–229.

Eaton, R., Ampong, F., Barnacle, J., Beesley, J., Bultman, D., Cookson, L., Cragg, S., Depalma, J., Gambetta, A., Henningsson, B., Levi, M., Levy, C., Nilsson, T., Orlandi, E., 1989. An international collaborative marine trial to investigate the effect of timber substrate on the efficacy of CCA and CCB wood preservatives. Mater. Org. 24, 51–79.

Edlund, M.-L., 1994. Losses of preservatives from treated wood during service. Results from a questionnaire. In: The International Research Group on Wood Protection, IRG/WP 94-50031.

Edlund, M.-L., Nilsson, T., 1998. Testing the durability of wood. Mater. Struct. 31, 641–647.

ENV, 1995. ENV 1250-2:1995. (Withdrawn): Wood Preservatives – Methods for Measuring Losses of Active Ingredients and Other Preservative Ingredients from Treated Timber – Part 2: Laboratory Method for Obtaining Samples for Analysis to Measure Losses by Leaching into Water or Synthetic Sea Water. European Committee for Standardization, Brussels, Belgium.

ENV, 2001. ENV 807:2001. Wood Preservatives – Determination of the Effectiveness Against Soft Rotting Micro-Fungi and Other Soil Inhabiting Micro-Organisms. European Committee for Standardization, Brussels, Belgium.

ENV, 2002. ENV 12038:2002. Durability of Wood and Wood-Based Products. Wood-Based Panels. Method of Test for Determining the Resistance Against Wood-Destroying Basidiomycetes. European Committee for Standardization, Brussels, Belgium.

ENV, 2014. ENV 839:2014. Wood Preservatives. Determination of the Protective Effectiveness Against Wood Destroying Basidiomycetes. Application by Surface Treatment. European Committee for Standardization, Brussels, Belgium.

EOTA, 2015. Factory Made Thermal and/or Acoustic Insulation Products Made of Vegetable or Animal Fibres. European Assessment document EAD 040005-00-1201. European Technical Assessments, Brussels.

Engelund, E.T., Klamer, M., Venås, T.M., 2010a. Acquisition of sorption isotherms for modified woods by the use of dynamic vapour sorption instrumentation. Principles and Practice. In: The International Research Group on Wood Protection, IRG/WP 10-40518, Stockholm.

Engelund, E.T., Thygesen, L.G., Hoffmeyer, P., 2010b. Water sorption in wood and modified wood at high values of relative humidity. Part 2: appendix. Theoretical assessment of the amount of capillary water in wood microvoids. Holzforschung 64, 325–330.

Engelund, E.T., Thygesen, L.G., Svensson, S., Hill, C.A.S., 2013. A critical discussion of the physics of wood-water interactions. Wood Sci. Technol. 47, 141–161.

Esser, P.M., van der Sloot, H.A., Suitela, W.L.D., 2001. Harmonisation of leaching tests: leaching behavior of wood. Heron 46 (4), 239–252.

European Commission, 2003. Directive 2003/2/EC of 6 January 2003 Relating to Restrictions on the Marketing and Use of Arsenic (10th Adaptation to Technical Progress to Council Directive 76/769/EEC). Book 9.1.2003.

Evans, F.G., 1987. Leaching from CCA-treated wood to food, drinking-water and silage. In: The International Research Group on Wood Protection, IRG/WP 87-3433, Stockholm.

Evans, F.G., 2004. Monitoring a Timber Bridge in Norway. In: The International Research Group on Wood Protection, IRG/WP 04-40282.

Evans, F.G., Edlund, M.-L., 1993. Leaching from field test stakes. Results from two different methods of analysis. In: The International Research Group on Wood Protection, IRG/WP 93-50013.

Evans, F.G., Nossen, B., Edlund, M.-L., 1994. Leaching from field test stakes. Part 2: the distribution in and leaching from different parts of test stakes. In: The International Research Group on Wood Protection, IRG/WP 94-50026.

Fackler, K., Schwanninger, M., Gradinger, C., Hinterstoisser, B., Messner, K., 2006. Assessing fungal decay of spruce and beech wood using near infrared spectroscopic techniques. Lenzinger Berichte 86, 9–13.

Feci, E., Mannucci, M., Palanti, S., 2013. Diagnostic evaluation of insect attack on existing timber structures: a review of some case studies. Adv. Mater. Res. 778, 281–288.

Feio, A., Machado, J.S., 2015. In-situ assessment of timber structural members: combining information from visual strength grading and NDT/SDT methods—a review. Construct. Build. Mater. 101, 1157–1165.

Flory, P.J., Rehner, J., 1943. Statistical theory of chain configuration and physical properties of high polymers. Ann. N. Y. Acad. Sci. 44, 419–429.

Fortino, S., Genoese, A., Nunes, L., Palma, P., 2013. Numerical modelling of the hygro-thermal response of timber bridges during their service life: a monitoring case-study. Construct. Build. Mater. 47, 1225–1234.

Franke, B., Widmann, R., Müller, A., Tannert, T., 2013. Assessment and monitoring of the moisture content of timber bridges. In: 2nd International Conference on Timber Bridges, 30th September–3rd October 2013, Las Vegas.

Fredriksson, M., Johansson, P., 2016. A method for determination of absorption isotherms at high relative humidity levels: measurements on lime-silica brick and Norway spruce (*Picea abies* (L.) Karst.). Drying Technol. 34, 132–141.

Fruhwald, E., Thelandersson, S., Fulop, L., Toratti, T., 2008. Robustness Evaluation of Failed Timber Structures. COST Office, ETH Zurich.

Fujii, Y., 2001. Detection of termite attack using acoustic emission monitoring: feasibility of AE monitoring for the ecological study of wood-attacking insects. Jpn. J. Environ. Entomol. Zool. 2 (1), 21–31.

Fujii, Y., Yanase, Y., 2001. Nondestructive evaluation of decay and insect attack in wood using acoustic emission (AE) monitoring and a radar technique, tools for maintaining wood in outdoor applications. In: High-Performance Utilization of Wood for Outdoor Uses. Wood Research Institute Kyoto University, Kyoto, pp. 145–160.

Fujii, Y., Fujiwara, Y., Yanase, Y., Okumura, S., Narahara, K., Ngatsuma, T., Yoshimura, T., Imamura, Y., 2007. Nondestructive detection of termites using a millimeter-wave imaging technique. For. Prod. J. 57 (10), 75–79.

García-Valcárcel, A.I., Bravo, I., Jiménez, C., Tadeo, J.L., 2004. Influence of leaching medium and drying time between successive leaching periods on the emission of chromium, copper, and boron from treated wood. Environ. Toxicol. Chem. 23 (11), 2682–2688.

Gellerich, A., Bollmus, S., Militz, H., 2015. How does the test methodology influence the outcome of durability testing of thermally modified wood. In: The International Research Group on Wood Protection, IRG/WP 15-40699.

Geya, Y., Kimura, T., Fujisaki, H., Terada, Y., Kose, K., Haishi, T., Gemma, H., Sekozawa, Y., 2013. Longitudinal NMR parameter measurements of Japanese pear fruit during the growing process using a mobile magnetic resonance imaging system. J. Magn. Reson. 226, 45–51.

Gobakken, L.R., Alfredsen, G., 2016. Susceptibility of wood substrates to *Aurebasidium pullulans* at different temperatures. In: The International Research Group on Wood Protection, IRG/WP 16-10863.

Gobakken, L.R., Whist, C.M., Høibø, O.A., Hovde, P.J., Larnøy, E., 2009. Assessment of mould growth on coated wood – methods and applications. In: The International Research Group on Wood Protection, IRG/WP 09-20423.

Gobakken, L.R., Høibø, O.A., Solheim, H., 2010. Factors influencing surface mould growth on wooden claddings exposed outdoors. Wood Mater. Sci. Eng. 5, 1–12.

Graf, E., Manser, P., Rezzonico, S., Zgraggen, B., 1993. Persistence of active ingredients in treated wood. In: IRG/WP 93-50001/20, Cannes-Mandelieu, France. 16 pp.

Graf, E., Manser, P., Lanz, B., 1998. Water-based wood preservatives for curative treatment of insect-infested spruce constructions'. In: The International Research Group on Wood Protection, IRG/WP 98-30171.

Green, B., Jones, P.D., Schimleck, L.R., Nicholas, D.D., Shmulsky, R., 2010. Rapid assessment of southern pine decayed by *G. trabeum* by near infrared spectra collected from the radial surface. Wood Fiber Sci. 42 (3), 1–10.

Habicht, J., Häntzschel, D., Wittenzellner, J., 2003. Influence of different fixation and ageing procedures on the leaching behaviour of copper from selected wood preservatives in laboratory trials. In: The International Research Group on Wood Protection, IRG/WP 03-20264.

Hæggström, E., Koponen, T., Karppinen, T., Saranpää, P., Serimaa, R., 2006. Ultrasonic study on hysteresis in modulus of elasticity in Norway spruce as a function of year ring. In: Thompson, D.O., Chimenti, D.E. (Eds.), Review of Progress in Quantitative Nondestructive Evaluation. AIP Conference Proceedings 820. vol. 25. American Institute of Physics, Melville, pp. 1366–1369.

Hameury, S., Lundstrom, T., 2004. Contribution of indoor exposed massive wood to a good indoor climate: in situ measurement campaign. Energy Build. 36 (3), 281–292.

Havermans, J.B.G.A., Homan, W.J., Boonstra, M.J., 1993. The shower test method – a leaching test for assessing preservative losses from treated timber under simulated open storage conditions. In: The International Research Group on Wood Protection, IRG/WP 93-50001/04.

Hedley, M.E., 1983. Practical considerations in assessing the importance of biodeterioration of board materials and its prevention. Biodeterioration 5, 117–126.

Herman, G.T., 1980. Image Reconstruction from Projections – The Fundamentals of Computerized Tomography. Academic Press, New York.

Herring, I.J., Dickinson, D.J., 1999. The use of organic wood preservatives in round contact and the suitability of laboratory test procedures to determine their efficacy. In: The International Research Group on Wood Protection, IRG/WP/99-20175.

Herring, I.J., Dickinson, D.J., Gray, S.M., Carey, J.K., 1997. An investigation of the factors influencing the rate of deterioration of timber samples due to microfungi in laboratory tests. International Research Group for Wood Preservation Document, IRG/WP 97-20116.

Hill, C.A.S., 2006. Wood Modification. Chemical, Thermal and Other Processes. John Wiley & Sons Ltd., New York. ISBN: 978-0-470-02172-9.

Hingston, J.A., Collins, C.D., Murphy, R.J., Lester, J.N., 2001. Leaching of chromated copper arsenate wood preservatives: a review. Environ. Pollut. 111, 53–66.

Hoang, C.P., Kinney, K.A., Corsi, R.L., Szaniszlo, P.J., 2009. Resistance of green building materials to fungal growth. Int. Biodeter. Biodegr. 64, 104–113.

Hoffmeyer, P., Thygesen, L.G., Engelund, E.T., 2011. Equilibrium moisture content in Norway spruce during the first and second desorptions. Holzforschung 65, 875–882.

Hon, D.N.-S., 1996. Chemical Modification of Lignocellulosic Materials. Marcel Dekker Inc., New York. ISBN: 0-8247-9472-9.

Honda, A., Kanjo, Y., Kimoto, A., Koshii, K., Kashiwazaki, S., 1991. Recovery of copper, chromium, and arsenic compounds from the waste preservative-treated wood. In: The International Research Group on Wood Protection, IRG/WP 91-3651.

Howick, C.D., Creffield, J.W., 1983. A rapid bioassay technique with subterranean termites. In: The International Research Group on Wood Protection, IRG/WP 1188.

HSE, 2001. Guidelines on the Efficiency Data Requirements for Approval of Non-Agricultural Pesticide Products – Wood Preservatives. Health and Safety Executive, London.

Huang, Y., Gram, A., Fang, P., 2008. UV-Degradation of IPBC in Natural Water Sample. Final Report. Department of Science, Systems and Models (NSM), Roskilde University, 35 pp.

Hukka, A., Viitanen, H., 1999. A mathematical model of mould growth on wooden material. Wood Sci. Technol. 33, 475–485.

Humar, M., Petrič, M., Pohleven, F., Šentjurc, M., Kalan, P., 2002. Changes in EPR spectra of wood impregnated with copper-based preservatives during exposure to several wood-rotting fungi. Holzforschung 56 (3), 229–238.

Humar, M., Thaler, N., Melcher, E., 2014. Copper and chromium leaching from wood impregnated with chromium-copper containing preservatives: results of different studies. In: The International Research Group on Wood Protection, IRG/WP 14-50300.

Imamura, Y., 1993. Estimation of the fungal resistance of wood composites for structural use. Curr. Jpn. Mater. Res. 11, 75–84.

Imamura, Y., 1994. Strength loss in wood composites and biological failure in gluelines. In: Proceedings from the Adhesives and Bonded Wood Symposium No. 4735. Forest Products Society, pp. 184–193.

ISO, 1977. ISO 3998:1977. Textiles – Determination of Resistance to Certain Insect Pests. International Organization for Standardization, Geneva, Switzerland.

ISO, 2010. ISO 13822:2010. Bases for Design of Structures – Assessment of Existing Structures. Reference Number 13822:2010(E). International Organization for Standardization, Geneva, Switzerland.

ISO, 2016. ISO 4628-1:2016. Paints and Varnishes – Evaluation of Degradation of Coatings – Designation of Quantity and Size of Defects, and of Intensity of Uniform Changes in Appearance – Part 1: General Introduction and Designation System. International Organization for Standardization, Geneva, Switzerland.

Jackson, D., Savory, J.G., 1968. Decay resistance of wood fibre building boards and particle boards. Int. Biodeter. Bull. 4 (2), 83–88.

Jacobs-Schönwandt, D., Mathies, H., Abraham, W.-R., Pritzkow, W., Stephan, I., Noll, M., 2010. Biodegradation of a biocide (Cu-*N*-cyclohexyldiazenium dioxide) component of a wood preservative by a defined soil bacterial community. Appl. Environ. Microbiol. 76 (24), 8076–8083.

Jarvis, B.B., Miller, J.D., 2005. Mycotoxins as harmful indoor air contaminants. Appl. Microbiol. Biotechnol. 66 (4), 367–372.

Jenner, H.A., Rajagopal, S., Van der Velde, G., Daud, M.S., 2003. Perforation of ABS pipes by boring bivalve *Martesia striata*: a case study. Int. Biodeter. Biodegr. 52, 229–232.

Jiang, J., Lu, J., Cai, Z., 2012. The vibrational properties of Chinese fir wood during moisture sorption process. BioResources 7, 3585–3596.

Jin, L., Preston, A.F., 1993. Depletion of preservatives from treated wood: Results from laboratory, fungus cellar and field tests. In: The International Research Group on Wood Protection, IRG/WP/93-50001-07.

JIS, 1998. JIS K 1571:1998. Superseded by JIS K 1571 (2004): Test Methods for Determining the Effectiveness of Wood Preservatives and Their Performance Requirements. Japanese Industrial Standards Committee.

Johansson, S., Wadsö, L., Sandin, K., 2010. Estimation of mould growth levels on rendered facades based on surface relative humidity and surface temperature measurements. Build. Environ. 45, 1153–1160.

Johansson, P., Ekstrand-Tobin, A., Svensson, T., Bok, G., 2012. Laboratory study to determine the critical moisture level for mould growth on building materials. Int. Biodeter. Biodegr. 73, 23–32.

Johansson, P., Bok, G., Ekstrand-Tobin, A., 2013. The effect of cyclic moisture and temperature on mould growth on wood compared to steady state conditions. Build. Environ. 65, 178–184.

Johnson, B.R., Lebow, S.T., 1996. Relative tolerance of CCA by larvae and adults of the common shipworm, *Bankia gouldi*. Mater. Org. 30, 73–78.

Jones, E.B.G., Kühne, H., Trussell, P.C., Turner, R.D., 1972. Results of an international cooperative research programme on the biodeterioration of timber submerged in the sea. Mater. Org. 7, 93–118.

Jones, M., Aptaker, P.S., Cox, J., Gardiner, B.A., McDonald, P.J., 2012. A transportable magnetic resonance imaging system for in situ measurements of living trees: the Tree Hugger. J. Magn. Reson. 218, 133–140.

Jorge, L., Dias, A., 2013. X-Lam panels in swimming-pool building – monitoring the environment and the performance. Adv. Mater. Res. 778, 779–785.

Jüngel, P., Melcher, E., Peek, R.-D., 1998. The non-uniform uptake of chromium and copper during the impregnation of wood using the example of a CCB-salt. In: The International Research Group on Wood Protection, IRG/WP 98-20137.

Kak, A.C., Slaney, M., 2001. Principles of Computerized Tomographic Imaging. Society of Industrial and Applied Mathematics, Philadelphia, PA.

Kasal, B., 2010. In-situ assessment of structural timber: state-of-the-art, challenges and future directions. Adv. Mater. Res. 133–134, 43–52.

Kasal, B., Tannert, T. (Eds.), 2011. In-Situ Assessment of Structural Timber. RILEM State-of-the-Art Reports. Springer, Dordrecht.

Kelly, M.W., Hart, C.A., 1970. Water vapor sorption rates by wood cell walls. Wood Fiber Sci. 1, 270–282.

Kennedy, M.J., Collins, P.A., 2001. Leaching of preservative components from pine decking treated with CCA and copper azole, and interactions of leachates with soils. In: The International Research Group on Wood Protection, IRG/WP 01-50171.

Kern, M., McGeehan, J.E., Streeter, S.D., Martin, R.N.A., Besser, K., Elias, L., Eborall, W., Malyon, G.P., Payne, C.M., Himmel, M.E., Schnorr, K., Beckham, G.T., Cragg, S.M., Bruce, N.C., McQueen-Mason, S.J., 2013. Structural characterization of a unique marine animal family 7 cellobiohydrolase suggests a mechanism of cellulase salt tolerance. Proc. Natl. Acad. Sci. U. S. A. 110, 10189–10194.

Kerner-Gang, W., 1987. Testing the resistance of plywood and particle board against wood destroying basidiomycetes. In: Proceedings of the I.U.F.R.O. Wood Protection Subject Group 1987, pp. 87–101.

King, A.J., Cragg, S.M., Li, Y., Dymond, J., Guille, M.J., Bowles, D.J., Bruce, N.C., Graham, I.A., McQueen-Mason, S.J., 2010. Molecular insight into lignocellulose digestion by a marine isopod in the absence of gut microbes. Proc. Natl. Acad. Sci. U. S. A. 107, 5345–5350.

Klüppel, A., Cragg, S.M., Militz, H., Mai, C., 2015. Resistance of modified wood to marine borers. Int. Biodeter. Biodegr. 104, 8–14.

Krus, M., Kilian, R., Sedlbauer, K., 2007. Mould growth prediction by computational simulation on historical buildings. In: Padfield, T., Borchersen, K. (Eds.), Museum, Microclimates. National Museum of Denmark, Copenhagen. ISBN: 978-877602-080-4.

Kühne, H., 1968. Laboratoriumsprüfung der natürlichen Widerstandsfähigkeit von drei Tropenholzarten gegen Holzbohrasseln der Gattung *Limnoria*. Mater. Org. 3, 107–118.

Kühne, H., Becker, G., 1970. Laboratoriumsversuche über die Wirkung küpferhaltiger Schutzsalzgemische auf die Holzbohrassel *Limnoria tripunctata* Menzies. Mater. Org. 5, 307–319.

Lanata, F., 2015. Analysis of the long-term behavior of a timber truss structure: the case of the ESB building. In: SHATIS15, Wroclaw.

Larsen, H., Enjily, V., 2009. Practical Design of Timber Structures to Eurocode 5. Thomas Telford Ltd., London, p. 272.

Larsson Brelid, P., Brischke, C., Pilgård, A., Hansson, M., Westin, M., Rapp, A.O., Jermer, J., 2011. Methods of field data evaluation – time versus reliability. In: The International Research Group on Wood Protection, IRG/WP/11-20466.

Lea, R.G., 1982. Contribution to the testing of wood based board materials. In: The International Research Group on Wood Protection, IRG/WP/2176.

Lea, R.G., Bravery, A.F., 1986. Laboratory assessment of the fungal resistance of wood based board materials. Mater. Org. 21 (2), 101–122.

Lebow, S., 1996. Leaching of Wood Preservative Components and Their Mobility in the Environment – Summary of Pertinent Literature. General Technical Report FPL-GTR-93. Forest Products Laboratory, 36 pp.

Lebow, S., Foster, D., 2005. Environmental concentrations of copper, chromium, and arsenic released from a chromated-copper-arsenate- (CCA-C-) treated wetland boardwalk. For. Prod. J. 55 (2), 62–70.

Lebow, S.T., Lebow, P.K., Foster, D.O., 2000. Environmental Impact of Preservative Treated Wood in a Wetland Boardwalk. Res. Pap. FPL-RP-582. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 126 pp.

Lebow, S., Cooper, P., Lebow, P., 2004. Variability in evaluating environmental impacts of treated wood. In: Proceedings of the Environmental Impacts of Preservative-Treated Wood Conference, Orlando, FL, 15 pp.

Lehmann, H.L., Mannes, D., 2012. Wood investigations by means of radiation transmission techniques. J. Cult. Herit. 13S, 35–43.

Leicester, R.H., 2001. Engineered durability for timber construction. Prog. Struct. Eng. Mater. 3, 216–227.

Leiße, B., 2002. Holzbauteile richtig geschützt. Langlebige Holzbauten durch konstruktiven Holzschutz. DRW Verlag. ISBN: 3-87181-356-7.

Lenz, M., Creffield, J.W., 1993. A below ground exposure method for determining the resistance of woody and non-woody materials to attack by subterranean termites. In: The International Research Group on Wood Protection, IRG/WP 93-10012.

Lenz, M., Creffield, J.W., Barrett, R.A., 1992. An improved field method for assessing the resistance of woody and non woody materials to attack by subterranean termites. Mater. Org. 27 (2), 89–115.

Lenz, M., Creffield, J.W., Evans, T.A., Kard, B., Vongkaluang, C., Sornnuwat, Y., Lee, C.-Y., Yoshimura, T., Tsunoda, K., 2012. Resistance of polyamide and polyethylene cable sheathings to termites in Australia, Thailand, USA, Malaysia and Japan: a comparison of four field assessment methods. Int. Biodeter. Biodegr. 66 (1), 53–62.

Lesar, B., Humar, M., 2016. Results of the monitoring of the pollutants in recovered wood in Slovenia. Technical report, 24 p. (in Slovenian).

Lesar, B., Kralj, P., Zlindra, D., Kancilija, V., Humar, M., 2008. Comparison of standard procedures for estimation of biocides leaching from impregnated wood. In: Zbornik gozdarstva in lesarstva, vol. 86, pp. 59–64. ISSN 0351-3114 [Tiskana izd.] (in Slovenian).

Li, W., Van Den Bulcke, J., Mannes, D., Lehmann, E., De Windt, I., Dierick, M., Van Acker, J., 2014. Impact of internal structure on water resistance of plywood studied using neutron radiography. Construct. Build. Mater. 73, 171–179.

Liese, J., 1954. Holzschutz. W Liese & C Gröger. VEB Verlag Technik, Berlin.

Liese, T., Bahmani, M., Melcher, E., 2013. Quantification of copper and chromium in field stakes after different exposure times: Remaining metal content and distribution. In: The International Research Group on Wood Protection, IRG/WP/13-50291.

Luchetti, M., 2016. Linee guida per il monitoraggio strutturale degli edifice in legno. Federlegno-Arredo, Milano.

Lupsea, M., Tiruta-Barna, L., Schiopu, N., Schoknecht, U., 2013. Modelling inorganic and organic biocide leaching from CBA-amine (Copper–Boron–Azole) treated wood based on characterisation leaching tests. Sci. Total Environ. 461–462, 645–654.

Machado, J.S., 2013. In situ evaluation of the reference properties of structural timber members. use of available tools and information. Adv. Mat. Res. 778, 137–144.

Machek, L., Militz, H., Sierra-Alvarez, R., 2001. The use of an acoustic technique to assess wood decay in laboratory soil-bed tests. Wood Sci. Technol. 34 (6), 467–472.

Mannes, D., 2009. Non-Destructive Testing of Wood by Means of Neutron Imaging in Comparison With Similar Methods (Doctoral Thesis). EHT, Zurich.

Mannes, D., Lehmann, H.L., 2007. Neutron imaging versus standard X-ray densitometry as method to measure tree ring wood density. Trees 21, 605–612.

Mannes, D., Sonderegger, W., Hering, S., Lehmann, E., Niemz, P., 2009. Non-destructive determination and quantification of diffusion processes in wood by means of neutron imaging. Holzforschung 63, 589–596.

Mantanis, G.I., Young, R.A., Rowell, R.M., 1994. Swelling of wood. Part 1. Swelling in water. Wood Sci. Technol. 28, 119–134.

McNatt, J.D., 1984. Static bending properties of structural wood-based panels: large panel versus small specimen tests. For. Prod. J. 34 (4), 50–54.

Meijer, M., Militz, H., 2000. Moisture transport in coated wood. Part 1: analysis of sorption rates and moisture content profiles in spruce during liquid water uptake. Holz Roh Werkst. 58, 354–362.

Meijer, M., Militz, H., 2001. Moisture transport in coated wood. Part 2: influence of coating type, film thickness, wood species, temperature and moisture gradient on kinetics of sorption and dimensional changes. Holz Roh Werkst. 58, 467–475.

Melcher, E., Müller, J., 2016. Bewitterung vermeiden. Bauen mit Holz. 3, 26–29.
Melcher, E., Wegen, H.-W., 2000. The remaining concentration of inorganic wood preservative components in EN 252 stakes after ground contact. In: The International Research Group on Wood Protection, IRG/WP/00-50159.
Melcher, E., Peek, R.-D., Schoknecht, U., Wegner, R., 2004. Depletion of boron and copper from CCB treated test specimens using different leaching protocols. In: The International Research Group on Wood Protection, IRG/WP/04-50208.
Menon, R.S., MacKay, A.L., Hailey, J.R.T., Bloom, M., Burgess, A.E., Swanson, J.S., 1987. An NMR determination of the physiological water distribution in wood during drying. J. Appl. Polym. Sci. 33, 1141–1155.
Menzies, R.J., 1957. The marine borer family Limnoriidae (Crustacea, Isopoda). Bull. Mar. Sci. Gulf Caribb. 7, 101–201.
Meyer, L., Brischke, C., 2015. Interpretation of moisture monitoring data – relevance of moisture content thresholds for fungal decay. In: The International Research Group on Wood Protection, IRG/WP/15-10839.
Meyer, L., Brischke, C., Rieken, J., 2013. Testing wood durability in 27 differently severe above-ground exposure conditions. The International Research Group on Wood Protection Document, IRG/WP/13-20517.
Meyer, L., Brischke, C., Preston, A., 2014. Testing the natural durability of timber exposed above ground – a review. Wood Mater. Sci. Eng. http://dx.doi.org/10.1080/17480272.2014.983163.
Meyer, L., Brischke, C., Treu, A., Larsson-Brelid, P., 2015. Critical moisture conditions for fungal decay of modified wood by basidiomycetes as detected by pile tests. Holzforschung 70 (4), 331–339.
Miura, M., Fujii, Y., Okumura, S., Yoshimura, T., Imamura, Y., Maekawa, T., Suzuki, K., 2014. Detection of hydrogen and methane from feeding activity of termites using a gas analyser. In: Proceedings of the 5th International Wood Science Symposium, Kyoto, pp. 151–156.
Moghaddam, A.H., Mulligan, C.N., 2007. Leaching of heavy metals from chromated copper arsenate (CCA) treated wood after disposal. Waste Manag. 28, 628–637.
Molnar, S., Dickinson, D.J., Murphy, R.J., 1996. Accelerated testing for out of ground contact using natural biological preconditioning. In: The International Research Group on Wood Protection, IRG/WP/96-20088.
Molnar, S., Dickinson, D.J., Murphy, R.J., 1997. Accelerated testing for out of ground contact using natural biological preconditioning: part 2. In: The International Research Group on Wood Protection, IRG/WP/97-20108.
Morgan, J.W.W., Purslow, D.F., 1973. Volatile losses of wood preservatives. In: The International Research Group on Wood Protection, IRG/WP/73-236.
Morsing, N., Lindegaard, B., 2004. Development of a Method for Characterising: Leaching of Active Ingredients from Preservative-Treated Timber. Stage 2 & 3: Laboratory Testing and Comparison with Semi-Field Testing. Final Report, Nord test Project 1622-03, pp. 1–15.
Morsing, N., Klamer, M., Seidel, B., Wittenzellner, J., Maier, M., Habicht, J., 2010. Comparison of laboratory and semi-field tests for the estimation of leaching rates from treated wood – part 1: above ground (UC 3). In: The International Research Group on Wood Protection, IRG/WP/10-50274.
Mukhopadhyaya, P., Kumaran, K., Normandin, N., Goudreau, P., 2002. Effect of surface temperature on water absorption coefficient of building materials. J. Build. Phys. 26, 179–195.

Müller, J., Schmidt, H., Melcher, E., 2015. Evaluierung von frei bewitterten, tragenden Holzbauteilen ohne Erdkontakt, die mit Holzschutzmitteln behandelt wurden, vol. T 3322. Fraunhofer IRB Verlag. ISBN: 978-3-8167-9551-3. 298 p.

Ncube, E., Chungu, D., Kamdem, D.P., Musawa, K., 2012. Use a of short span field test to evaluate termite resistance of Eucalyptus Grandis and Bobgunnia Madagascariensis in a tropical environment. BioResources 7 (3), 4098–4108.

Nicholas, D.D., 1973. Wood Deterioration and Its Prevention by Preservative Treatments. Volume II: Preservatives and Preservative Systems. Syracuse University Press, Syracuse. ISBN: 0-8156-5037-X.

Nielsen, K.F., 2003. Mycotoxin production by indoor molds. Fungal Genet. Biol. 39 (2), 103–117.

Nilsson, T., Edlund, M.-L., 1995. Laboratory Versus Field Tests for Evaluating Wood Preservatives: A Scientific View, In: International Research Group for Wood Preservation, Document No. 95-20076.

Nordtest, 1989. NT BUILD 338 (Nordtest Method) Coatings: Mould Resistance. Nordtest, Denmark.

Norman, E., Henningsson, B., 1975. Description of a Trial with Wood Preservatives Against Marine Wood Boring Organisms. Reports, Book 118. The Swedish Wood Preservation Institute, Stockholm.

Nowak, T., Jasiénko, J., Hamrol-Bielecka, K., 2016. In situ assessment of structural timber using the resistance drilling method – evaluation of usefulness. Construct. Build. Mater. 102, 403–415.

Nurmi, A.J., 1990. Leachability of active ingredients from some CCA treated and creosoted poles in service. A progress report after 10 years testing. In: The International Research Group on Wood Protection, IRG/WP/90-3627, 8 pp.

OECD, 2003. Estimation of Emissions from Preservative – Treated Wood to the Environment: Laboratory Method for Wooden Commodities that are not covered and are in Contact with Ground, Fresh Water or Seawater (OECD Guideline Proposal).

OECD, 2007. OECD Guideline for the Testing of Chemicals, Section 3: Degradation and Accumulation, Organisation for Economic Cooperation and Development (OECD). Test No. 313: Estimation of Emissions from Preservative – Treated Wood to the Environment Laboratory Method for Wooden Commodities that are not Covered and are in Contact with Fresh Water or Seawater. Health and Safety Division Environment Directorate. doi:10.1787/9789264067370-en, 9 p.

Oevering, P., Matthews, B.J., Cragg, S.M., Pitman, A.J., 2001. Invertebrate biodeterioration of marine timbers above mean sea level along the coastlines of England and Wales. Int. Biodeter. Biodegr. 47, 175–181.

Oliver Villanueva, J.V., Albian-Perez, M.A., 2013. Advanced wireless sensors for termites detection in wood constructions. Wood Sci. Technol. 47, 269–280.

Ormondroyd, G., Spear, M., Curling, S., 2015. Modified wood: review of efficacy and service life testing. Constr. Mater. 168 (4), 187–203.

Papadopoulos, A.N., Hill, C.A.S., 2003. The sorption of water vapour by anhydride modified softwood. Wood Sci. Technol. 37, 221–231.

Pasanen, A.L., Kasanen, J.-P., Rautiala, S., Ikaheimo, M., Rantamaki, J., Kaariainen, H., Kalliokoski, P., 2000. Fungal growth and survival in building materials under fluctuating moisture and temperature conditions. Int. Biodeter. Biodegr. 46, 117–127.

Passarini, L., Malveau, C., Hernández, R.E., 2015. Distribution of the equilibrium moisture content in four hardwoods below fibre saturation point with magnetic resonance microimaging. Wood Sci. Technol. 49, 1251–1268.

Pechenik, J.A., Perron, F.E., Turner, R.D., 1979. The role of phytoplankton in the diets of adult and larval shipworms, *Lyrodus pedicellatus* (Bivalvia: Teredinidae). Estuaries 2, 58–60.

Pel, L., Ketelaars, A.A.J., Adan, O.G.C., 1993. Determination of moisture diffusivity in porous media using scanning neutron radiography. Int. J. Heat Mass Transf. 36, 1261–1267.

Perdoch, W., Mazela, B., Waśkiewicz, A., 2014. Wood treatment with organosilanes – perspective for IPBC stabilization. In: The International Research Group on Wood Protection, IRG/WP 14-30641.

Peters, B.C., Creffield, J.W., Eldridge, R.H., 2002. Susceptibility testing protocol for powderpost beetles in Australia. In: The International Research Group on Wood Protection, IRG/WP 02-20242.

Peylo, A., 1995. Auswaschung von Boraten aus chemisch geschütztem Holz (Dissertation). Universität Hamburg, 145 pp.

Peylo, A., Willeitner, H., 1999. Five years leaching of Boron. In: The International Research Group on Wood Protection, IRG/WP 99-30195.

Piazza, M., Riggio, M.P., 2008. Visual strength-grading and NDT of timber in traditional structures. J. Build. Appraisal Impact Descr. 3, 267–296.

Pitman, A.J., Jones, E.B.G., Jones, M.A., Oevering, P., 2003. An overview of the biology of the wharf borer beetle (*Nacerdes melanura* L., Oedemeridae) a pest of wood in marine structures. Biofouling 19, 239–248.

Porteous, J., Ross, P., 2013. Designers' Guide to Eurocode 5: Design of Timber Buildings. EN 1995-1-1. ICE Publishing, London. 205 p.

Preston, A.F., McKaig, P.A., Walcheski, P.J., 1985. Termite resistance of treated wood in an above ground field test. In: The International Research Group on Wood Protection, IRG/WP 2241.

Radivojevic, S.A., Cooper, P., 2007. Effects of CCA-C preservative retention and wood species on fixation and leaching of Cr, Cu, and As. Wood Fiber Sci. 39 (4), 591–602.

Rapp, A.O., (Ed.), 2001. Review on heat treatments of wood. In: Proceedings of the Special Seminar Held in Antibes, France, COST E 22, Brussels. ISBN: 92-894-1656-4.

Rapp, A.O., Peek, R.D., Sailer, M., 2000. Modelling the moisture induced risk of decay for treated and untreated wood above ground. Holzforschung 54, 111–118.

Richardson, B.A., 1978. Wood Preservation. The Construction Press, New York. ISBN: 0 904406 75X.

Rinn, F., 2012. Basics of micro-resistance drilling for timber inspection. Holztechnologie 53 (3), 24–29.

Rinn, F., 2013. Practical application of micro-resistance drilling for timber inspection. Holztechnologie 54 (4), 32–38.

Ross, R.J., DeGroot, R.C., Nelson, W.J., Lebow, P.K., 1997. The relationship between stress wave transmission characteristics and the compressive strength of biologically degraded wood. For. Prod. J. 47 (5), 89–93.

Ruddick, J.N.R., 2008. Biocide depletion: chemical, physical, and photodegradation. In: Schultz, T.P., Militz, H., Freeman, M.H., Goodell, B., Nicholas, D.D. (Eds.), Development of Commercial Wood Preservatives. ACS Symposium Series, vol. 982. ISBN: 978-0-8412-3951-7.

Rüther, P., 2011. Wood Weathering from a Service Life Perspective (Doctoral Theses). Norwegian University of Science and Technology, p. 187.

Rutherford, D., Reay, R.C., Ford, M.G., 1979. The development of a screening method to estimate contact toxicity of pyrethroids against wood-boring marine crustacea, *Limnoria* spp. Pestic. Sci. 10, 527–530.

Sandak, A., Sandak, J., Zborowska, M., Prądzyński, W., 2010. Near infrared spectroscopy as a tool for archaeological wood characterization. J. Archeol. Sci. 37 (9), 2093–2101.

Sandak, A., Sandak, J., Riggio, M., 2015. Estimation of physical and mechanical properties of timber members in service by means of infrared spectroscopy. Construct. Build. Mater. 101, 1197–1205.

Sandberg, K., Salin, J.-G., 2012. Liquid water absorption in dried Norway spruce timber measured with CT-scanning and viewed as a percolation process. Wood Sci. Technol. 46, 207–219.

Savory, J.G., 1969. Testing the fungus resistance of board materials. Mater. Org. (Suppl. 2), 49–56.

Schabacker, A., Alfredsen, G., Gobakken, L.R., Militz, H., Flæte, P.O., 2013. System treatments of *Pinus sylvestris* – influence on moisture, decay and discoloration. In: The International Research Group on Wood Protection, IRG/WP 13-30612.

Schmidt, O., 2006. Wood and Tree Fungi. Springer, Berlin/Heidelberg.

Schoknecht, U., Wegner, R., Horn, W., Jann, O., 2003. Emission of biocides from treated materials: test procedures for water and air. Environ. Sci. Pollut. Res. 10 (3), 154–161.

Schoknecht, U., Wegner, R., Melcher, E., 2004a. Experiences with the OECD guideline proposals for the estimation of emissions from preservative treated wood in the environment. In: The International Research Group on Wood Protection, IRG/WP 04-50209.

Schoknecht, U., Wegner, R., Melcher, E., Seidel, B., Kussatz, C., Maletzki, D., 2004b. The influence of test parameters on the emission of biocides from preservative-treated wood in leaching tests. Umweltforschungsplan Bundesministeriums Umwelt, Naturschutz und Reaktorsicherheit. Förderkennzeichen (UFOPLAN) 20367441. Bundesanstalt für Materialprüfung und -forschung, Abschlussbericht, Berlin. 161 pp.

Schoknecht, U., Gruycheva, J., Mathies, H., Bergmann, H., Burkhardt, M., 2009. Leaching of biocides used in facade coatings under laboratory test conditions. Environ. Sci. Technol. 43, 9321–9328.

Schultz, T.P., Nicholas, D.D., Pettry, D.E., Kim, M.G., 2000. Effect of soil parameters on biocide depletion: laboratory and field studies of water- and emulsion-borne preservatives. In: The International Research Group on Wood Protection, IRG/WP/00-30234.

Schultz, T.P., Nicholas, D.D., Pettry, D.E., 2002. Depletion of CCA-C from ground-contact wood: results from two field sites with significantly different soils. Holzforschung 56, 125–129.

Schultz, T.P., Militz, H., Freeman, M.H., Goodell, B., Nicholas, D.D. (Eds.), 2008. Non-biocidal chemicals and processes to protect wood. In: Development of Commercial Wood Preservatives. ACS Symposium Series, vol. 982. ISBN: 978-0-8412-3951-7.

Sedighi-Gilani, M., Griffa, M., Mannes, D., Lehmann, E., Carmeliet, J., Derome, D., 2012. Visualization and quantification of liquid water transport in softwood by means of neutron radiography. Int. J. Heat Mass Transf. 55, 6211–6221.

Sedlbauer, K., 2001. Prediction of Mould Fungus Formation on the Surface of and Inside Building Components (Thesis). Holzkirchen.

Serrano, E., Enquist, B., Vessby, J., 2014. Long Term In-Situ Measurements of Displacement, Temperature and Relative Humidity in a Multi-Storey Residential CLT-Building. WCTE, Quebec City.

Sexton, C.M., Corden, M.E., Morrell, J.J., 1993. Assessing fungal decay of wood by small scale toughness tests. Wood Fiber Sci. 25 (4), 375–383.

Shillinglaw, A.W., Moore, D.D., 1947. Report of Marine Borer Survey in New Guinea Waters. Council for Scientific and Industrial Research, Melbourne.

Si, A., Bellwood, O., Alexander, C.G., 2002. Evidence for filter-feeding by the wood-boring isopod, *Sphaeroma terebrans* (Crustacea: Peracarida). J. Zool. 256, 463–471.

Sierra-Alvarez, R., 2007. Fungal bioleaching of metals in preservative-treated wood. Process Biochem. 42, 798–804.

Skaar, C., 1988. Wood-Water Relations. Springer, Berlin.

Slevin, C., Westin, M., Lande, S., Cragg, S., 2015. Laboratory and marine trials of resistance of furfurylated wood to marine borers. In: Hughes, M., Raukari, L., Uimonen, T., Militz, H., Junge, B. (Eds.), Proceedings of the Eighth European Conference on Wood Modification. Aalto University, Espoo.

Sorin, E., Lanata, F., Boudaud, C., 2016. Behaviour of Timber Structures Under Variable Environment Through Long-Term Monitoring. WCTE, Wien.

Sousa, H.S., Sørensen, J.D., Kirkegaard, P.H., Branco, J.M., Lourenço, P.B., 2013. On the use of NDT data for reliability-based assessment of existing timber structures. Eng. Struct 56, 298–311.

Southwell, C.R., Bultman, J.D., 1971a. Biological Deterioration of Woods in Tropical Environments. Part 3 – Chemical Wood Treatments for Long-Term Marine Borer Protection. NRL Report, Book 7345, Naval Research Laboratory, Washington, DC.

Southwell, C.R., Bultman, J.D., 1971b. Natural resistance of untreated woods over long periods of immersion in tropical waters. Biotropica 3, 81–107.

Stefanowski, B.K., Curling, S.F., Mansour, E., Ormondroyd, G.A., 2015. Development of a rapid screening method to determine the susceptibility to mould growth of novel construction and insulation products. In: The International Research Group on Wood Protection, IRG/WP/15-20562.

Stefanowski, B.K., Curling, S.F., Ormondroyd, G.A., 2017. A rapid screening method to determine the susceptibility of bio-based construction and insulation products to mould growth. Int. Biodeter. Biodegr. 116, 124–132.

Štefko, J., Reinprecht, L., 2004. Dřvěně Stavby. Konstrukce Ochrana a Údržba. JAGA, Bratislava. ISBN: 80-88905-95-8.

Stephan, I., Leithoff, H., Peek, R.-D., 1996. Microbial conversion of wood treated with salt wood preservatives. Mater. Org. 30 (3), 179–199.

Stook, K., Tolaymat, T., Ward, M., Dubey, B., Townsend, T., Solo-Gabriele, H., Bitton, G., 2005. Relative leaching and aquatic toxicity of pressure-treated wood using batch leaching tests. Environ. Sci. Technol. 39, 155–163.

Suchy, M., Virtanen, J., Kontturi, E., Vuorinen, T., 2010. Impact of drying on wood ultrastructure observed by deuterium exchange and photoacoustic FT-IR spectroscopy. Biomacromolecules 11, 515–520.

Suzuki, K., 1999. A real scale evaluation method and results on termite resistance of housing wall systems and floor frames. In: The International Research Group on Wood Protection, IRG/WP 99-10314.

Takahashi, N., Mikami, N., Matsuda, T., Miyamoto, J., 1985. Photodegradation of the pyrethroid insecticide cypermethrin in water and on soil surface. J. Pestic. Sci. 10, 629–642.

Temiz, A., Yildiza, U.C., Nilsson, T., 2006. Comparison of copper emission rates from wood treated with different preservatives to the environment. Build. Environ. 41, 910–914.

Terziev, N., 1997. Fungal discoloration of kiln- and air-dried scots pine lumber in aboveground testing and its assessment by digital image processing. Forest Products J. 47 (9), 43–46.

Thaler, N., Humar, M., 2014. Copper leaching from copper-ethanolamine treated wood: comparison of field studies and laboratory standard procedures. BioResources 9 (2), 3038–3051.

Thaler, N., Humar, M., 2016. Performance of copper treated poles and posts after three to fifteen years of exposure. In: The International Research Group on Wood Protection, IRG/WP 16-20595.

Thelanderson, S., Isaksson, T., 2013. Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions. Build. Environ. 65, 18–25.

Thelandersson, S., Larsen, H. (Eds.), 2003. Timber Engineering. Wiley, London. 456 p.

Tiemann, H.D., 1906. Effect of moisture upon strength and stiffness of wood. USDA For. Serv. Bull. 70, 144.

Townsley, P.M., Richy, R.A., Trussell, P.C., 1966. The laboratory rearing of the shipworm, *Bankia setacea* (Tryon). Proc. Natl. Shellfish. Assoc. 56, 49–52.

Turner, R.D., 1971. Identification of marine wood boring molluscs. In: Jones, E.B.G., Eltringham, S.K. (Eds.), Marine Borers and Fouling Organisms of Wood. OECD, Paris.

UNI, 2004. UNI 11119:2004. Cultural Heritage, Wooden Artefacts. Load-Bearing Structures – On Site Inspections for the Diagnosis of Timber Members. Italian Organization for Standardization (UNI).

Van Acker, J., Stevens, M., 1997. A new concept for the evaluation of wood durability for out of ground contact using accelerated L-joint testing. In: The International Research Group on Wood Protection, IRG/WP 97-20123.

Van Acker, J., De Windt, I., Li, W., Van den Bulcke, J., 2014. Critical parameters on moisture dynamics in relation to time of wetness as factor in service life prediction. In: The International Research Group on Wood Protection, IRG/WP14-20555, Stockholm.

Van Acker, J., Van den Bulcke, J., De Windt, I., Colpaert, S., Li, W., 2015. Moisture dynamics of modified wood and the relevance towards decay resistance. In: Hughes, M., et al. (Eds.), Proceedings of the 8th European Conference on Wood Modification, 26–27th October. Helsinki, Finland, pp. 44–55.

Van den Bulcke, J., Van Acker, J., Stevens, M., 2005. Image processing as a tool for assessment and analysis of blue stain discoloration of coated wood. Int. Biodeter. Biodegr. 56, 178–187.

Van den Bulcke, J., Van Acker, J., Stevens, M., 2006. Assessment of blue-stain resistance according to the EN 152 and a reverse test method using visual and computer-aided techniques. Int. Biodeter. Biodegr. 57, 229–238.

Van den Bulcke, J., Van Acker, J., De Smet, J., 2009. An experimental set-up for real-time continuous moisture measurements of plywood exposed to outdoor climate. Build. Environ. 44, 2368–2377.

Van Eetvelde, G., 1998. Chemical and Environmental Appraisal of Wood Preservation with Copper-Based Formulations in High Hazard Applications (Ph.D. Thesis). University Gent, 237 pp.

Van Houts, J., Wang, S., Shi, H., Pan, H., Kabalka, G.W., 2004. Moisture movement and thickness swelling in oriented strandboard, part 1. Analysis using nuclear magnetic resonance imaging. Wood Sci. Technol. 38, 617–628.

Van Krevelen, D.W., Hoftijzer, P.Z., 1976. Properties of Polymers, second ed. Elsevier Scientific Publishing, New York.

Van Nieuwenhuijzen, E.J., Sailer, M.F., Gobakken, L.R., Adan, O.C.G., Punt, P.J., Samson, R.A., 2015. Detection of outdoor mould staining as biofinish on oil treated wood. Int. Biodeterior. Biodegrad. 105, 215–227.

Vidović, N., 1981. Short-term test method with accelerated infection of Basidiomycetes in wood. In: The International Research Group on Wood Protection, IRG/WP 81-2155.

Viitanen, H., Ritschkoff, A., 1991. Mould growth in pine and spruce sapwood in relation to air humidity and temperature (Report No. 221). The Swedish University of Agricultural Sciences, Department of Forest Products, Uppsala, 40 p + app 9 p.

Viitanen, H., Toratti, T., Makkonen, L., Peuhkuri, R., Ojanen, T., Ruolkolainen, L., Räisänen, J., 2010. Towards modelling of decay risk of wooden materials. Eur. J. Wood Wood Prod. 68, 303–313.

Voight, J.R., 2015. Xylotrophic bivalves: aspects of their biology and the impacts of humans. J. Moll. Stud. 81, 175–186.

Volkmer, T., Schwarze, F.W.M.R., 2008. Diffusionsverhalten von IPBC in wasserbasierten Beschichtungssystemen auf Holzfassaden (Diffusion behavior of IPBC in water based coatings on wooden facades). Holz Roh Werkst. 66, 181–189.

Wagenführ, A., Scholz, F., 2008. Taschenbuch der Holztechnik. Fachbuchverlag, Leipzig. pp. 81–82.

Wakeling, R., 2006. Above and below-ground depletion of copper, chromium and arsenic from *pinus radiata* and *Fagus sylvatica* at thirteen test sites in New Zealand and Australia. In: The International Research Group on Wood Protection, IRG/WP/06-30402.

Waldron, L., Cooper, P.A., 2010. Modeling of simultaneous three-dimensional leaching and chemical reaction of CCA components in unfixed wood exposed to water. Wood Sci. Technol. 44, 129–147.

Waldron, L., Cooper, P.A., Ung, T.Y., 2005. Prediction of long-term leaching potential of preservative-treated wood by diffusion modelling. Holzforschung 50 (5), 581–588.

Walker, J.C.F., 2006. Primary Wood Processing, second ed. Springer, Dordrecht.

Wang, P.C., Chang, S.J., 1986. Nuclear magnetic resonance imaging of wood. Wood Fiber Sci. 18, 308–314.

Wang, J.-H., Nicholas, D.D., Sites, L.S., Pettry, D.E., 1998. Effect of soil chemistry and physical properties on wood preservative leaching. In: The International Research Group on Wood Protection, IRG/WP/98-50111.

Wang, C.H., Leicester, R.H., Ngyen, M.N., 2008. Decay Above Ground. Manual No. 4, In: CSIRO Sustainable Ecosystems, Urban Systems Program, Highett, VIC.

Wang, W., Zhu, Y., Cao, J., Sun, W., 2015. Correlation between dynamic wetting behaviour and chemical components of thermally modified wood. Appl. Surf. Sci. 324, 332–338.

Warner, J.E., Solomon, K.R., 1990. Acidity as a factor in leaching of copper, chromium and arsenic from CCA-treated dimension lumber. Environ. Toxicol. Chem. 9, 1331–1337.

Watanabe, K., Lazarescu, C., Shida, S., Avramidis, S., 2012. A novel method of measuring moisture content distribution in timber during drying using CT scanning and image processing techniques. Dry. Technol. 30, 256–262.

Westin, M., Rapp, A.O., Nilsson, T., 2004. Durability of pine modified by 9 different methods. In: The International Research Group on Wood Protection, IRG/WP 04-40288, Stockholm.

Westin, M., Brelid, P.L., Nilsson, T., Rapp, A.O., Dickerson, J.P., Lande, S., Cragg, S., 2016. Marine borer resistance of acetylated and furfurylated wood – results from up to 16 years of field exposure. In: International Research Group on Wood Protection Document, IRG/WP 16-40756.

Wexler, A., Hasegawa, S., 1954. Relative humidity-temperature relationships of some saturated salt solutions in the temperature range 0 to 50°C. J. Res. Natl. Bur. Stand. 53, 19–26.

White, F.D., 1929. Studies on marine borers. 1. The toxicity of various substances on *Limnoria lignorum*. Contrib. Can. Biol. Fish. 4, 3–7.

Willeitner, H., 1965. The behaviour of wood particle board under attack by basidiomycetes – part 1. Decomposition of particle board by basidiomycetes. Holz Roh Werkst. 23 (7), 264–271.

Willeitner, H., 1973. Pollution in wood preservation – aspects and problems. In: The International Research Group on Wood Protection, IRG/WP/73-55.

Willems, W., 2014a. The water vapor sorption mechanism and its hysteresis in wood: the water/void mixture postulate. Wood Sci. Technol. 48, 499–518.

Willems, W., 2014b. Hydrostatic pressure and temperature dependence of wood moisture sorption isotherms. Wood Sci. Technol. 48, 483–498.
Willems, W., 2016. Equilibrium thermodynamics of wood moisture revisited: presentation of a simplified theory. Holzforschung. http://dx.doi.org/10.1515/hf-2015-0251.
Windt, C.W., Blümler, P., 2014. A portable NMR sensor to measure dynamic changes in the amount of water in living stems or fruit and its potential to measure sap flow. Tree Physiol. 35, 366–375.
Wischer, B., Willeitner, H., 1977. Untersuchungen über die Einwirkung von Regen bei frisch imprägnierten Kiefern-Masten im Hinblick auf mögliche Umweltbelastungen. Holz Roh Werkst. 35 (2), 79–84.
Zachary, A., Parrish, K.K., Bultman, J.D., 1983. Possible role of marine bacteria in providing the creosote resistance of *Limnoria tripunctata*. Mar. Biol. 75, 1–8.
Zahora, A., Jin, L., Preston, A., 2013. Update on "Sandwich" type above ground field test methods. In: The International Research Group on Wood Protection, IRG/WP 13-20506.
Zauer, M., Hempel, S., Pfriem, A., Mechtcherine, V., Wagenführ, A., 2014. Investigations of the pore-size distribution of wood in the dry and wet state by means of mercury intrusion porosimetry. Wood Sci. Technol. 48, 1229–1240.
Zelinka, S.L., Glass, S.V., Jakes, J.E., Stone, D.S., 2016. A solution thermodynamics definition of the fiber saturation point and the derivation of a wood–water phase (state) diagram. Wood Sci. Technol. 50, 443–462.

This page intentionally left blank

Modelling

8

8.1 Introduction

C. Brischke[*,†]
[*]Leibniz University Hannover, Hannover, Germany
[†]University of Göttingen, Göttingen, Germany

Service life planning and performance classification require well-functioning 'performance models'. In the following, an overview is provided about different approaches to adequately reflect the influence of biotic and abiotic factors on the performance of bio-based building materials.

The term 'performance model' is ambiguous to some extent in a double sense: on the one hand, 'performance' can be understood differently depending on the respective material, product, commodity and its application. On the other hand, the general meaning of 'model' is the schematic description of a system, theory or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics, but it is not determined, which factors will describe the command variable. Particularly for bio-based building materials, biological agents need consideration for service life modelling.

Depending on how much *a priori* information is available for a system, one can distinguish between black-box and white-box models, though these terms only describe extremes, and usually, a mathematical model is located somewhere in between. It appears trivial that using as much *a priori* information as possible increases the accuracy of a model, but nevertheless, for certain applications, it is also worth considering black-box models. For service life prediction, computer systems would be eligible that utilise preprogrammed logic to return output to the user, but the 'black-box' portion of such systems contains algorithms that the user does not see and thus does not need to know how to use the system. However, for modelling biological processes, this can cause severe problems, which is why 'white-box' models are usually preferable. A multitude of materials, potential data sources, design details, exposure conditions and abiotic and biotic agents come into consideration for service life prediction of wooden components and potentially for other bio-based materials. The existing knowledge about many of the relevant decay-influencing factors can be utilised only in white-box models in the following.

Ideally, a performance model should therefore be transparent and include traceable functional relationships to enable continual adjustment and implementing a steadily increasing amount of input data. Moreover, it needs to allow usage of data from different sources such as lab and field tests, *in situ* moisture recordings, commodity and in-service performance tests, surveys, questionings and case studies. Finally, the model should allow different limit states to be defined and target performance.

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00008-2
© 2017 Elsevier Ltd. All rights reserved.

Modelling is a relevant task in many different disciplines with significant overlaps between the latter. In the following, existing approaches and procedures will be presented with focus on mould development, hygrothermal performance, weathering, decay and the mechanical performance of bio-based building materials.

8.2 Mould development

E. Frühwald Hansson
Lund University, Lund, Sweden

8.2.1 Modelling approaches

Mould growth on building materials and in building envelope can be a big problem with both health and aesthetical aspects. The most important factors influencing mould growth are moisture, temperature, type of substrate and exposure time, whereas less important factors are, e.g. availability of mould spores, pH, light, oxygen and surface roughness (Vereecken and Roels, 2012). To be able to assess the risk for mould growth on building materials or in building envelope, several mould prediction models have been developed during recent years. Vereecken and Roels (2012) reviewed many of the available models ranging from simple models taking only one or two of the important mould influencing factors into account to models considering more or even all conceivable factors. In this chapter, only prediction models for mould growth on bio-based materials are considered, i.e. other models developed, e.g. for mould growth on malt agar and plaster or rendered facades, are not reported here.

A short overview of the presented mould development models is given in Table 8.1, showing which parameters are considered in the respective models.

8.2.2 Isopleth models

8.2.2.1 Sedlbauer's isopleth model

Sedlbauer (2001) created an isopleth system for use in mould risk prediction. Using measurement data from other researchers, covering different mould species and mainly optimum substrate, he found the most important mould species that germinate and grow at lowest relative humidity (*RH*) and temperature conditions and created isopleth graphs for germination time and mycelium growth on an optimum substrate (agar). Using the small amount of measurement data of mould growth on other substrates, he translated the existing curves to higher RH (as mould needs higher RH to germinate/grow on building materials compared with optimum substrate), thus creating isopleth graphs for different substrate groups. The isopleth graphs show, for example, the germination time for certain RH and temperature conditions and a limiting line below which no growth occurs, thus showing a safe region (see Figs. 8.1 and 8.2). The isopleth graphs can be easily used to predict risk or no risk for mould germination or growth for stationary conditions. For varying climate conditions, the risk of mould germination or growth can be predicted by summing up the effects of different short time intervals at certain temperature-relative humidity conditions according to

Table 8.1 Overview of mould models described (Vereecken and Roels, 2012)

Model	T	$T<0$	RH	Substrate	Germination	Growth	Growth delay	Simulation tool
Isopleth[a]	Yes	No	Yes	Yes	Yes	Yes	No	No
Mould germination graph[b]	Yes	No	Yes	Yes	Yes	Yes	No	No
Biohygrothermal model[c]	Yes	Slight growth	Yes	Yes	Yes	Yes	No	WUFI-Bio
VTT original[d]	Yes	No	Yes	Yes (wood)	Yes	Yes	Yes	Latenite
VTT updated[e]	Yes	No	Yes	Yes	Yes	Yes	Yes	Latenite
MRD model[f]	Yes	No	Yes	Yes	Yes	Yes[g]	Yes	WUFI add-on

Factors considered, T—influence of temperature, $T<0$—growth at low temperatures, RH—influence of relative humidity, substrate—influence of substrate, germination—prediction of germination, growth—prediction of growth, growth delay—influence of boundary conditions on growth delay and simulation tool—simulation tool that includes the model

[a] Sedlbauer (2001)
[b] Moon (2005)
[c] Krus *et al*. (2001)
[d] Hukka and Viitanen (1999)
[e] Viitanen *et al*. (2011)
[f] Thelandersson and Isaksson (2013)
[g] Thelandersson and Isaksson (2013) recommend not to use the model to predict mould growth but only mould germination and lower levels of mould growth, as the model was developed for this range.

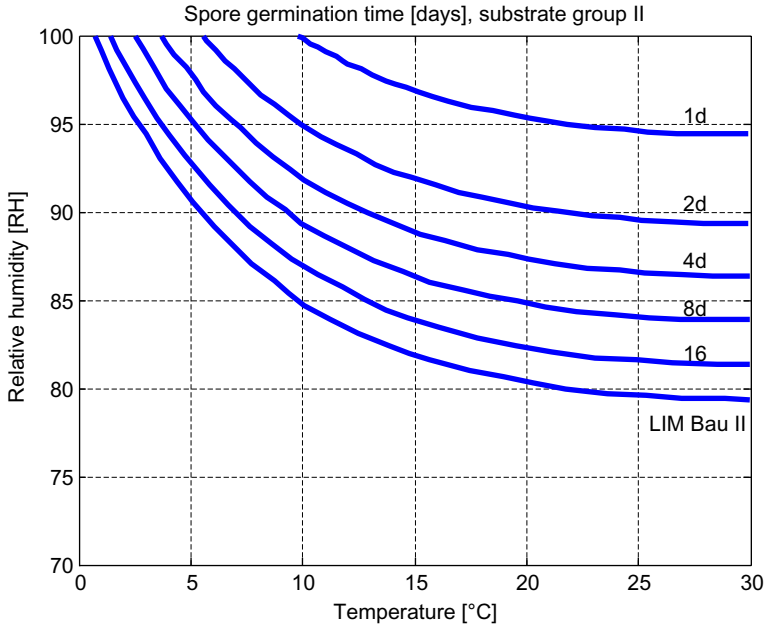


Fig. 8.1 Isopleth system for mould germination (Sedlbauer, 2001).

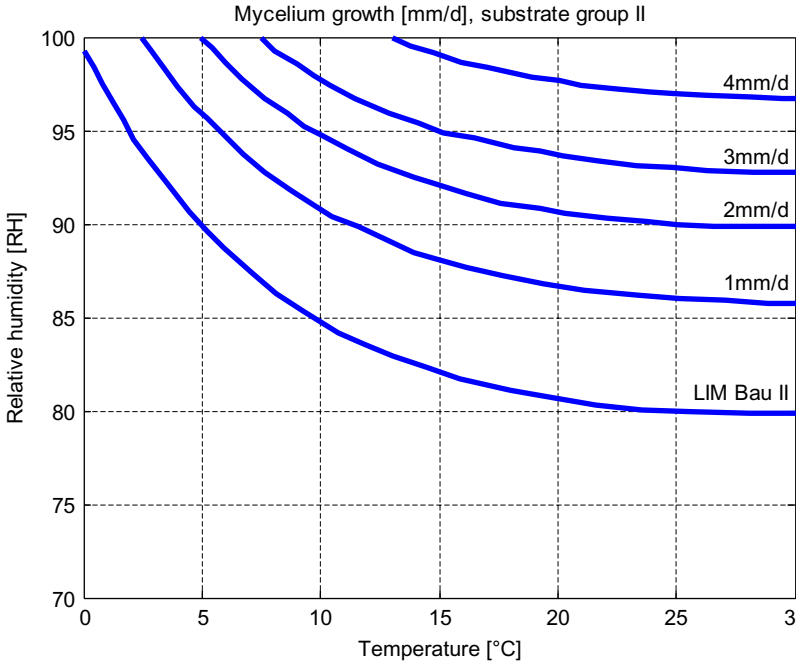


Fig. 8.2 Isopleth system for growth of mycelium (Sedlbauer, 2001).

Eq. (8.1). $M_{tot} \geq 1$ indicates mould germination/mould growth, whereas $M_{tot} < 1$ indicates no germination/growth. However, this method does not account for setback due to unfavourable conditions, i.e. it overpredicts the risk for mould germination/growth:

$$M_{tot} = \sum_{i=1}^{n} \frac{1}{D_i\left(\mathrm{RH}_i; T_i\right) \cdot 24} \tag{8.1}$$

where

M_{tot} = mould indicator
D_i = 'dose' (days) shown by the isotherms for certain climatic conditions of hourly relative humidity RH_i and hourly temperature T_i (see Fig. 8.1, which shows 'doses' of 1, 2, 4, 8 and 16 days).

8.2.2.2 Mould germination graph method

The mould germination graph method presented by Moon (2005) allows for predicting mould germination under fluctuating conditions. The method also includes setback due to unfavourable conditions, which Sedlbauer's method (Sedlbauer, 2001) is lacking as described above.

The mould germination graph method uses mould germination isopleths for *Aspergillus restrictus*, produced by Smith and Hill (1982) and Ayerst (1969) giving one of the lowest isopleths for mould species commonly found in buildings (see Fig. 8.3). For each day, the surface conditions measured (or simulated) will be assigned to one of the groups I–VII, and the accumulated days in this group and the required germination time for this group are recorded (see Table 8.2 for an example). When the accumulated days equal the required days, there is risk for mould (mouldy day). For consecutive days in the same group, more mouldy days will occur. However, if the surface conditions are assigned to a higher group (longer germination time), for lower groups (shorter germination time), the process will start over from zero. If the surface conditions are outside the favourable range, no germination will occur, and the accumulated exposure time is set to zero. This contrasts with other models (e.g. VTT model and MRD model), which have a limited setback, however, not starting off at zero, and thus, the mould germination graph method might result in non-conservative predictions.

The mould germination graph method can e.g. be used in hygrothermal studies of the building envelope to determine the effects of certain parameters or to find the best solution (least risk for mould) under certain climatic conditions.

8.2.3 Biohygrothermal model/WufiBio

The biohygrothermal model developed by Krus *et al.* (2001) was the first model that could predict mould growth under changing humidity and temperature conditions. The model predicts the moisture balance of a mould spore depending on surrounding unsteady boundary conditions (RH and temperature), (Sedlbauer, 2001; Krus *et al.*, 2001). At which moisture contents (*MC*) mould will germinate is based on the lowest isopleths for mould germination (LIM, as described by e.g. Sedlbauer, 2001). The biohygrothermal model of the spore is used as a second step after modelling the moisture balance of the building envelope with a hygrothermal model (e.g. WUFI). The spore is modelled one-dimensionally and isothermally, using a moisture storage function

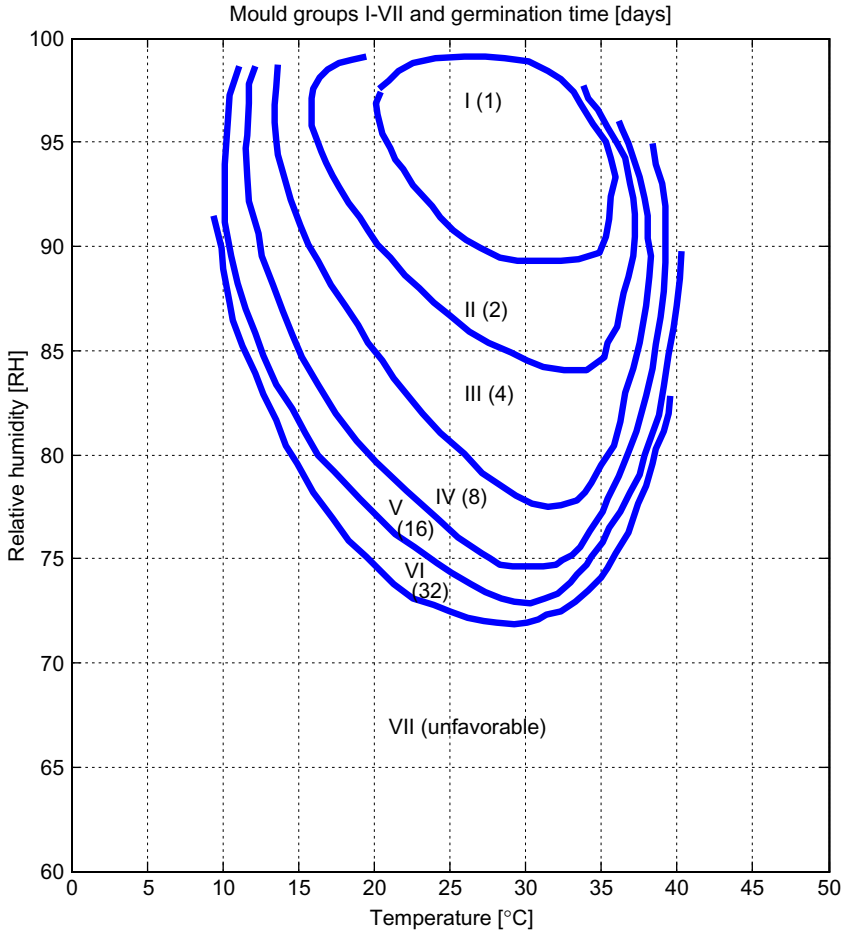


Fig. 8.3 Mould germination graph, showing each group (I–VII) with temperature, RH and required exposure time for the initiation of mould germination (Smith and Hill, 1982; Moon, 2005).

(from bacteria, Rubel, 1997) and moisture-dependent vapour diffusion resistance of the spore (based on tests by Smith and Hill (1982)) as input parameters. However, there is still a lot of information lacking, e.g. on the influence of the substrate on the spores' MC and the exact values of the material properties of the spore (moisture retention curve and vapour resistance curve of the spore wall), thus resulting in a need for further research. When a limiting MC is reached in the spore, mould growth is expected to occur, thus assessing the risk for mould growth rather than the actual growth processes. The biohygrothermal model of the spore was validated by modelling the roof of a test house where mould growth had been observed on some vapour retarders, and the correlation between test results and the model was good. For the WUFI-Bio add-on, the modelling results are usually conservative, thus resulting in an over- prediction of mould growth.

Table 8.2 **Example of the application of the germination graph method (Moon, 2005)**

			Boundary condition groups							
Day	*T*(°C)	RH (%)	I (1)	II (2)	III (4)	IV (8)	V (16)	VI (32)	VII (∞)	Mouldy days
1	20	70	0	0	0	0	0	0	1	No
2	25	80	0	0	1	1	1	1	2	No
3	23	85	0	0	2	2	2	2	3	No
4	26	90	0	1	3	3	3	3	4	No
5	30	95	1	2*	4*	4	4	4	5	Yes
6	22	85	0	0	5*	5	5	5	6	Yes
7	18	97	0	1	6*	6	6	6	7	Yes
8	25	80	0	0	7*	7	7	7	8	Yes
9	18	97	0	1	8*	8*	8	8	9	Yes
10	20	70	0	0	0	0	0	0	10	No
11	25	80	0	0	1	1	1	1	11	No
12	18	97	0	1	2	2	2	2	12	No

Six groups (I–VI) with favourable conditions and group VII with unfavourable conditions. In parenthesis, the required number of days until mould germination is presented for the groups. Twelve days of simulated data showing accumulated days in each group. Values marked with * indicate mould germination for that group on that day. This example shows 5 days with mould risk during a 12-day period

8.2.4 VTT model

At VTT in Finland, Hukka and Viitanen (1999) modelled mould growth based on tests of mould growth on small specimens of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) sapwood under constant and varying humidity conditions (testing reported in Viitanen and Ritschkoff (1991)). Mould was measured based on an index with 7 levels ($M = 0 \ldots 6$), described in Hukka and Viitanen (1999), and it is this mould index (M) that is calculated by the model (Eqs. 8.2–8.9). The critical relative humidity necessary for initiation of mould growth depends on the temperature and is modelled by a polynomial function (Eq. 8.2). The mould index M under conditions favourable for mould growth (i.e. when $\mathrm{RH} \geq \mathrm{RH}_{crit}$) is calculated as in Eq. (8.3) (with in-data from Eqs. 8.4–8.8). The effect of non-favourable conditions (setback, decreasing activity of the mould, when $\mathrm{RH} < \mathrm{RH}_{crit}$) can be modelled as in Eq. (8.9), where the size of the setback is dependent on the duration of the dry period. The authors of this model themselves partly question this setback approach, as the model gives no setback for moderately long dry periods (6–24 h), whilst there is an effect for both shorter and longer dry periods. They point out that this setback approach is based on only a few experiments and may be used in the lack of better information on the setback.

The model has been validated by the authors in both constant and cycling humidity conditions, and the error is low.

$$\mathrm{RH}_{crit} = \begin{cases} -0.00267T^3 + 0.16T^2 - 3.13T + 100 & \text{when } T \leq 20°\mathrm{C} \\ \mathrm{RH}_{\min} = 80\% & \text{when } T > 20°\mathrm{C} \end{cases} \tag{8.2}$$

$$\frac{dM}{dt} = \frac{k_1 k_2}{7 t_{M=1}} \tag{8.3}$$

where

$$k_1 = \begin{cases} 1 & \text{when } M \leq 1 \\ \dfrac{2}{t_{M=3} / t_{M=1} - 1} & \text{when } M > 1 \end{cases} \tag{8.4}$$

$$t_{M=1} = \exp\left(-0.68 \ln T - 13.9 \ln \mathrm{RH} + 0.14W - 0.33SQ + 66.02\right) \tag{8.5}$$

$$t_{M=3} = \exp\left(-0.74 \ln T - 12.72 \ln \mathrm{RH} + 0.06W + 61.5\right) \tag{8.6}$$

$$k_2 = \max\left\{1 - \exp\left[2.3\left(M - M_{\max}\right)\right]; 0\right\} \tag{8.7}$$

$$M_{\max} = 1 + 7\frac{\mathrm{RH}_{crit} - \mathrm{RH}}{\mathrm{RH}_{crit} - 100} - 2\left(\frac{\mathrm{RH}_{crit} - \mathrm{RH}}{\mathrm{RH}_{crit} - 100}\right)^2 \tag{8.8}$$

$$\frac{dM}{dt} = \begin{cases} -0.00133 & \text{when } t - t_1 \leq 6\,\mathrm{h} \\ 0 & \text{when } 6\,\mathrm{h} \leq t - t_1 \leq 24\,\mathrm{h} \\ -0.000667 & \text{when } t - t_1 > 24\,\mathrm{h} \end{cases} \tag{8.9}$$

where

M = mould index (-)
RH_{crit} = critical relative humidity (below which no mould growth happens) (%)
RH = relative humidity (%)
T = temperature (°C)
t = time (days)
M_{max} = maximum mould index possible for a certain RH after long time
k_1, k_2 = correction coefficients
$t_{M=1}$ = response time (weeks) necessary for initiation of mould growth (mould level 1) under constant humidity and temperature conditions
$t_{M=3}$ = response time (weeks) necessary for first visual mould growth (M = 3)
W = wood species (0 = Scots pine and 1 = Norway spruce)
SQ = surface quality (0 = resawn and 1 = original kiln dried)
t-t_1 = length of the period outside growth conditions (low temperature/ low RH) (hours)

As the model described above is only valid for wood surfaces, it was updated to also taking into account other building materials (Viitanen *et al.*, 2011). Based on tests with different building materials reported by Salminen *et al.* (2009), mould growth on those materials is compared with mould growth on resawn pine sapwood, which is used as reference material in the model. Whilst the general equations of the original model are still valid, some of the in-data parameters have changed. Thus, a new set of equations according to the new model, valid for different building materials, is presented below (Eqs. 8.10–8.16), modelling mould growth by Eqs. (8.10)–(8.14) and decline of mould growth by Eqs. (8.15)–(8.16). New factors have been evaluated by testing and expert estimation and are compiled in Tables 8.3 and 8.4 (Viitanen *et al.*, 2011). It should be observed that the decline classes (in Table 8.4) taking into account the decline of mould growth during unfavourable conditions are based on relatively few tests, and C_{mat} should therefore be seen as a first approximation. This updated model was found to satisfactorily predict the risk for mould growth for a range of typically used building materials (Viitanen *et al.*, 2011).

$$RH_{crit} = \begin{cases} -0.00267T^3 + 0.16T^2 - 3.13T + 100 & \text{when } T \le 20°C \\ RH_{min} & \text{when } T > 20°C \end{cases} \tag{8.10}$$

$$\frac{dM}{dt} = \frac{k_1 k_2}{7 t_{M=1}} \tag{8.11}$$

$$t_{M=1} = \exp\left(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02\right) \tag{8.12}$$

$$k_2 = \max\left\{1 - \exp\left[2.3\left(M - M_{max}\right)\right]; 0\right\} \tag{8.13}$$

$$M_{max} = A + B\frac{RH_{crit} - RH}{RH_{crit} - 100} - C\left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2 \tag{8.14}$$

Table 8.3 Parameters for different sensitivity classes of the updated VTT model (Viitanen *et al.*, 2011)

Sensitivity class	Material example	k_1		k_2 (M_{max})			RH$_{min}$
		$M<1$	$M\geq1$	*A*	*B*	*C*	
Very sensitive	Scots pine sapwood	1	2	1	7	2	80
Sensitive	Norway spruce, glued wooden boards, *PUR* with paper surface	0.578	0.386	0.3	6	1	80
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	0.072	0.097	0	5	1.5	85
Resistant	PUR polished surface	0.033	0.014	0	3	1	85

Table 8.4 Classification of relative mould index decline (Viitanen *et al.*, 2011)

Decline classes	C_{mat}
Pine in original model, short periods	1.0
Significant relevant decline	0.5
Relatively low decline	0.25
Almost no decline	0.1

$$\frac{dM}{dt_{mat}} = C_{mat}\frac{dM}{dt_{pine}} \tag{8.15}$$

$$\frac{dM_{pine}}{dt} = \begin{cases} -0.00133 & \text{when } t-t_1 \leq 6\text{h} \\ 0 & \text{when } 6\text{h} \leq t-t_1 \leq 24\text{h} \\ -0.000667 & \text{when } t-t_1 > 24\text{h} \end{cases} \tag{8.16}$$

where

M = mould index (-)
RH$_{crit}$ = critical relative humidity (below which no mould growth happens) (%)
RH = relative humidity (%)
T = temperature (°C)
t = time (days)
M_{max} = maximum mould index possible for a certain RH after long time
k_1, k_2 = correction coefficients
$t_{M=1}$ = response time (weeks) necessary for initiation of mould growth (mould level 1) under constant humidity and temperature conditions
W = wood species (0 = Scots pine and 1 = Norway spruce)
SQ = surface quality (0 = resawn and 1 = original kiln dried)
t-t_1 = length of the period outside growth conditions (low temperature/ low RH) (hours)

8.2.5 Mould resistance design (MRD) model

The MRD model was developed by researchers at Lund University, Sweden. A first model (Isaksson *et al.*, 2010) was based on laboratory tests reported by Viitanen and Ritschkoff (1991). The dose-response model predicted mould for input values of daily averages of coupled temperature and RH. An updated version of the model, the MRD model, which is presented here, is based on newer laboratory data by Johansson *et al.* (2013). The MRD model (Thelandersson and Isaksson, 2013) predicts the onset of mould growth for material surfaces exposed to time variations (12 h average values) of coupled temperature and relative humidity (Eqs. 8.18–8.21), to take into account diurnal (day-night) changes. The model is based on laboratory tests in both constant and cyclic climate conditions (Johansson, 2012), resulting in a critical dose D_{crit}, which is equal to the time until the limit state 'onset of mould growth' (sparse but clearly established growth) is reached (Johansson, 2012). The critical dose D_{crit} (Eq. 8.17) depends on the material and surface conditions and the climate exposure (reference climate) during the testing. Favourable conditions (warm/humid climate) lead to increasing dose (Eqs. 8.20–8.21), whereas unfavourable conditions (dry/cold climate) lead to a setback of the biological process as could be seen in both testing and observations in buildings. This setback is introduced in the model as a negative dose (Eqs. 8.22, 8.23), and a safe region (no mould risk) is defined for $\phi < 75\%$ or $T < 0.1°C$. The output of the model is the MRD-index I_{MRD} (Eq. 8.24), which is a measure distinguishing between onset of mould ($I_{MRD} \geq 1$) and low/no risk for mould ($I_{MRD} < 1$) during the investigated time interval. The MRD model was derived for onset of mould and should be used to predict this early stage of mould growth. It has been shown that the model is somewhat conservative compared with testing, and it can be used e.g. to evaluate mould risk in hygrothermal modelling of the building envelope (the MRD model is e.g. available as add-on to WUFI). Values for the critical dose D_{crit} for some commercial available materials can be found in Table 8.5.

$$D_{crit} = D\left(t_{crit}\right) = \sum_{1}^{2t_{crit}} D_{\phi}\left(\phi_{ref,i}\right) \cdot D_{T}\left(T_{ref,i}\right) = t_{crit} \tag{8.17}$$

$$D_{12} = D_{\phi}\left(\phi_{12}\right) \cdot D_{T}\left(T_{12}\right) \tag{8.18}$$

$$D\left(t\right) = D\left(0.5 n_{12}\right) = \sum_{1}^{n_{12}} D_{12i} = \sum_{1}^{n_{12}} D_{\phi}\left(\phi_{12i}\right) \cdot D_{T}\left(T_{12i}\right) \tag{8.19}$$

$$D_{\phi}\left(\phi_{12}\right) = 0.5 \cdot \exp\left[15.5 \cdot \ln\left(\frac{\phi_{12}}{90}\right)\right] \quad \text{for } 75 < \phi \leq 100\% \tag{8.20}$$

$$D_{T} = \begin{cases} \exp\left[2.0 \cdot \ln\left(\dfrac{T_{12}}{20}\right)\right] & \text{if } 0.1\langle T \leq 30°C \text{ and } D_{\phi} \rangle 0 \\ 1.0 & \text{if } D_{\phi} > 0 \end{cases} \tag{8.21}$$

Table 8.5 Critical dose D_{crit} for some materials, surfaces and treatments (Bok *et al.*, 2012, 2013; Johansson and Jermer, 2010; Thelandersson *et al.*, 2014)

Material	Surface	Treatment	D_{crit} (days)
Norway spruce	planed, commercial quality	-	17
	sawn	-	10
		Boron compound	>70
Scots pine	planed	-	12
	sawn	-	8
		Class NTR AB	>50
Modified wood		Furfurylated Scots pine WPG (~45 %)	35
		Thermowood D (212°C), Scots pine	12
		Acetylated radiata pine (~20 %)	>50
		Wood polymer composite (50% pine fibres/50% polypropylene)	>50

$$D_{\phi}\left(\phi_{12}\right)=\begin{cases}-2.118+0.0286\cdot\phi_{12} & \text{for } 60<\phi_{12}\le 75\% \\ -0.4 & \text{for } \phi_{12}\le 60\%\end{cases} \tag{8.22}$$

$$D\left(\phi_{12},T_{12}\right)=-0.4 \quad \text{for } T_{12}<0.1°\text{C} \tag{8.23}$$

$$I_{MRD}\left(t\right)=\frac{D\left[\phi\left(t\right),T\left(t\right)\right]}{D_{crit}}<1 \tag{8.24}$$

where

D_{crit} = critical dose (days), equal to the time until onset of mould (days)
ϕ_{12} = average RH during 12 h period (%)
T_{12} = average temperature during 12 h period (°C)
D_{12} = half-day dose
D_{ϕ} = moisture - induced dose (days)
D_T = temperature-induced dose (-)
n_{12} = total number of 12 h periods within the time period t (days)
I_{MRD} = MRD index (-)

8.2.6 Reliability analysis

Several recent studies (e.g. Pietrzyk, 2015; Sadovský *et al.*, 2014) investigated the importance and effect of uncertainties in mould modelling. However, those studies usually use one of the mould models described above and use e.g. Monte Carlo simulations to investigate the effect of climatic uncertainties. To model uncertainties will always improve the simulation results as the user will get not only one result but also a range of possible results.

8.3 Hygro-thermal models

S. Fortino
VTT Technical Research Centre of Finland Ltd, Espoo, Finland

8.3.1 General aspects

Nowadays, the use of wood and other bio-based materials in the construction field is promoted by the growing request of environmentally friendly buildings. However, wood is a hygroscopic and biodegradable material, and consequently, the level of moisture content (MC) during the service life of a wood-based building has to be properly monitored to preserve the durability, serviceability and safety of the whole construction. In this context, the experimental research aims at providing efficient systems for the measurement of hygrothermal and biological variables in wood, whilst the focus of the computational research is to assess numerical techniques able to simulate the behaviour of wood under variable climates (Fragiacomo *et al.*, 2011; Svensson *et al.*, 2011; Fortino *et al.*, 2013; Ormarsson and Gíslason, 2016).

Herein, a review of some of the recent advances in hygrothermal modelling for wood is presented and suggestions for future work given. The development of accurate numerical methods for moisture transport is related to the need of a more detailed knowledge on the distribution of MC inside wooden elements. The risks for durability in wooden structures can increase due to the annual variations of relative humidity RH that increase the moisture penetration depth in timber elements exposed to variable climates (Svensson *et al.*, 2011). In addition, high daily variations of moisture at high levels of relative humidity can cause large moisture gradients close to external surfaces with the development of so-called moisture-induced stresses (*MIS*) and possible increase of crack risk (Fragiacomo *et al.*, 2011; Fortino *et al.*, 2013). These stresses can provide cracks in wooden components as, for example, glulam (Jönsson, 2005; Angst, 2012) and cross laminated timber (Gereke and Niemz, 2010). As shown by Fragiacomo *et al.* (2011) and Angst (2012), the moisture-induced stresses perpendicular to grain may exceed the tensile and compressive strength also in the absence of external mechanical loads. In those papers, the moisture transport modelling was based on a single-Fickian approach (as described in Section 8.3.2) in which the only variable is the MC.

The moisture-related degradation of timber structures during their service life has been an important topic within the COST Action E55 (modelling of the performance of timber structures) that ran between 2006 and 2011, along with the development of computational methods aiming at evaluating moisture gradients and moisture-induced stresses. Among the main results of that research, the use of numerical models based on the so-called multi-Fickian method was recommended by Svensson *et al.* (2011) for a more realistic representation of the moisture transport in wood. An interesting outcome of that paper was that daily humidity variations and large changes of humidity at high levels of RH provide higher moisture gradients and, consequently, higher MIS. The multi-Fickian method was particularly developed in the last decade (Frandsen, 2007 and related references). It describes the diffusion of water vapour in the cell lumens, the sorption of bound water and the diffusion of bound water in the cell walls. The

multi-Fickian-coupled differential problem is characterised by two variables: the bound water concentration and the water vapour concentration. In non-isothermal cases, the temperature T must also be considered as a variable of the moisture transport problem, whilst both the relative humidity and the temperature of the air are considered as loads on the wooden structure. In the presence of natural environmental conditions, a model for hysteresis of wood and other lignocelluloses is also needed, which uses at least two sorption isotherms to describe the phenomena of adsorption and desorption in wood (Frandsen, 2007). A multi-Fickian model with wood hysteresis for timber structures subjected to continuously varying climates was implemented and tested for glulam beams of timber bridges under Southern European climates (Fortino *et al.*, 2013) and, more recently, under Northern European climates (Fortino *et al.*, 2016).

Improved design of wooden structures accounting for possible moisture effects caused by significant variations of RH is important for their serviceability and safety in order to prevent structural failures related to the design phase (Frühwald *et al.*, 2007). Calculations of MIS for glulam beams of buildings were carried out by Fragiacomo *et al.* (2011), and MIS were also calculated for glulam beams of timber bridges exposed to Northern European weather conditions (Musci, 2016).

In the following sections, the single-Fickian and multi-Fickian models for moisture transfer in wood material used in the previous literature by the author and collaborators are described, and some examples of applications are provided.

8.3.2 Single-Fickian model

8.3.2.1 Governing equations

In the single-Fickian approach, the moisture transfer is modelled by using the 3-D Fick equation (Eq. 8.25, see Fortino *et al.* (2009)):

$$\partial \mathrm{MC} / \partial t = \nabla \cdot \left(D \nabla \mathrm{MC} \right) \tag{8.25}$$

where

MC = moisture content of wood
D = diffusion tensor of moisture transfer

This form of the Fick equation can be used when the density of wood is constant. For varying density, the variable concentration $c = \rho \mathrm{MC}$ instead of MC should be considered (where c represents the concentration in kg/m^3). The assumption of isotropic diffusion is usually made in literature, and only the diagonal coefficients of the matrix are considered to be non-zero. The moisture flow through the surface is given by the following equation (Eq. 8.26):

$$q_n = \rho_0 S \left(\mathrm{MC}_{air} - \mathrm{MC}_{surf} \right) \tag{8.26}$$

where

q_n = value of the flow across the boundary
ρ_0 = wood density in absolute dry conditions
S = surface emissivity

MC = moisture content on the wood surface
MC_{air} = equilibrium moisture content of wood corresponding to the air humidity

According to Fortino *et al.* (2009), the used expression is shown in Eq. (8.27):

$$MC_{air} = 0.01\left(\frac{-T\ln(1-RH)}{0.13\left(1-\frac{T}{647.1}\right)^{-6.46}}\right)^{\frac{1}{110T^{-0.75}}} \tag{8.27}$$

where

T = temperature of the air
RH = relative humidity of the air

Expressions for diffusion and surface emission parameters are provided by Fortino *et al.* (2009). A review on the material parameters for moisture transfer used in the literature is given by Angst (2012). Very recently, the described model was further developed for cases of MC above the fibre saturation point (*FPS*) in water traps by using a permeability tensor in place of the diffusion tensor; see Musci (2016).

8.3.2.2 Implementation in Abaqus code and applications

The single-Fickian model is easy to implement in finite element codes, such as Abaqus. In particular, the analogy between Fick's equation and the heat transfer equation available in Abaqus can be exploited as done by Fortino *et al.* (2009) who also presented the validation of the method for some cases of wood specimens.

The equations needed to describe the moisture flow in wood can be implemented in the Abaqus user subroutine DFLUX where both the flow magnitude and the rate of change of flow with respect to the current moisture content are calculated. By using this approach, the long-term calculations of moisture transport in wood are quite simple and fast (Fragiacomo *et al.*, 2011). In that paper, three typologies of wooden section (glulam, sawn timber and cross laminated timber), sheltered from rain and solar radiation, were tested under the effect of nine European climatic regions identified on the basis of Köppen-Geiger's classification. Moisture levels and moisture gradients were especially studied and the related moisture-induced stresses and the protective effect of coatings (see Fragiacomo *et al.*, 2011 for the details). Fig. 8.4 shows the average moisture levels during 10 years for a 115 x 240 mm^2 glued-laminated section made of 12 lamellas of 45 mm thickness in the zones of Lisbon (warm Mediterranean climate), Warsaw (temperate continental climate) and Rovaniemi (cool continental climate). The glulam section was sheltered from sun and rain. The relative humidity of the surrounding air was assumed to act on the bottom and vertical edges, whilst the top edge was blocked (Fig. 8.4, left). This type of boundary conditions is typical, for example, in timber beams supporting a flooring system. It can be observed that the amplitude of the average moisture content is higher for the cold climate of Rovaniemi. The numerical study carried out revealed that the larger yearly variations of relative humidity RH in Northern European climates (average values over 80 %) cause higher moisture gradients (and higher MIS) compared with the Southern European climates.

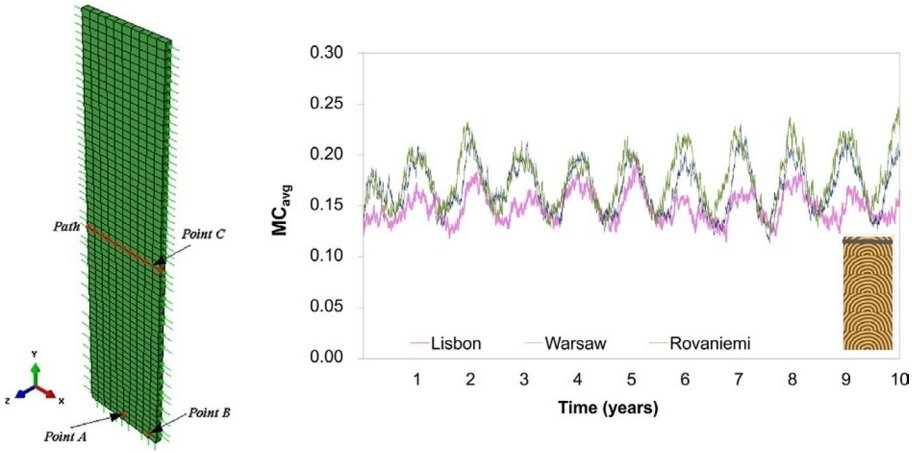


Fig. 8.4 Left, Abaqus model for the glulam section. Right, average moisture content (MC_{avg}) on the middle path of the section exposed to three different climates during 10 years (from 1999 to 2009).

In the same paper, the presence of a protective coating was found to represent an effective solution for the reduction of moisture gradients.

8.3.3 Multi-Fickian model

8.3.3.1 Governing equations

Following Fortino *et al.* (2013), the multi-Fickian model is based on three partial differential equations (Eqs. 8.28–8.30):

$$\frac{\partial c_b}{\partial t} = \nabla \cdot \left(\mathbf{D}_\mathrm{b} \nabla c_b \right) + \dot{c} \tag{8.28}$$

$$\frac{\partial c_v}{\partial t} = \nabla \cdot \left(\mathbf{D}_\mathrm{v} \nabla c_v \right) - \dot{c} \tag{8.29}$$

$$c_w \varrho \frac{\partial T}{\partial t} = \nabla \cdot \left(\mathbf{K} \nabla T \right) + \nabla \cdot \left(\mathbf{D}_\mathrm{b} \nabla c_b \right) h_b + \nabla \cdot \left(\mathbf{D}_\mathrm{v} \nabla c_v \right) h_\mathrm{v} + \dot{c} h_{bv} \tag{8.30}$$

where

c_b = unknown concentrations of bound water
c_v = unknown concentration of water vapour
$\mathbf{D}_\mathrm{b}$ = macroscopic diffusion tensor of bound water
$\mathbf{D}_\mathrm{v}$ = macroscopic diffusion tensor of water vapour
$\dot{c}$ = coupling term representing the sorption rate

Eq. (8.30) describes the energy conservation related to the unknown temperature T. $\mathbf{K}$ is the thermal conductivity tensor, h_b and h_v are the specific enthalpies of bound and vapour water, $h_\mathrm{bv} = h_\mathrm{b} - h_\mathrm{v}$ is the specific enthalpy of the water phase transition from the bound state to the vapour one *and* ρ is the dry density of wood whose specific heat is

c_w. The details on the above material parameters can be found in (Fortino *et al.*, 2013). Homogeneous Neumann boundary conditions for bound water concentration, water vapour concentration and temperature are used on the insulated surfaces (Eq. 8.31):

$$\nabla c_b = \mathbf{0}, \quad \nabla c_v = \mathbf{0}, \quad \nabla T = 0 \tag{8.31}$$

On the surfaces in contact with air, the boundary condition on the bound water concentration is assumed to be as shown in Eq. (8.32):

$$\nabla c_b = \mathbf{0} \tag{8.32}$$

And the fluxes of water vapour and heat fluxes are expressed as shown in Eq. (8.33):

$$-\boldsymbol{n} \cdot \boldsymbol{D}_v \nabla c_v = k_{\boldsymbol{v}} \left(c_v^{'} - c_v^{a} \right), \quad \boldsymbol{n} \cdot \boldsymbol{K} \nabla T = k_{\boldsymbol{T}} \left(T - T^{a} \right) \tag{8.33}$$

where

c_v^{a} = water vapour concentration in the surrounding ambient
T^{a} = temperature in the surrounding ambient
k_v = surface emission coefficient for water vapour
k_T = surface emission coefficient for temperature
$c_v^{'} = c_v / \varphi$ = concentration of water vapour

This last quantity is based on the volume of the cell lumens φ being the porosity, i.e. the volume of lumens with respect to that of the dry wood.

The sorption rate of equations is defined as in Eq. (8.34) (Frandsen, 2007):

$$\dot{c} = H_c \left(c_{bl} - c_b \right) \tag{8.34}$$

in which $c_{bl} = \rho_0 m_{bl}$ represents the bound water concentration in equilibrium with a given relative humidity RH, according to the Hailwood-Horrobin isotherm (Eq. 8.35):

$$m_{bl} = \mathrm{RH} / \left(f_{1\alpha} + f_{2\alpha} \mathrm{RH} + f_{3\alpha} \mathrm{RH}^2 \right); \alpha = a, d \tag{8.35}$$

where the subscripts (a and d) refer to adsorption and desorption, respectively, and RH is calculated as the ratio between vapour pressure and saturated vapour pressure (Fig. 8.5). The used shape parameters for the isotherm curves of adsorption and desorption are the ones proposed by Ahlgren for Norway spruce (see Frandsen, 2007). The parameters for the adsorption curve are reported in Table 8.6.

The moisture-dependent reaction rate function H_c of Eq. (8.35) and the other material parameters of multi-Fickian model and the hysteresis model of wood using the above two sorption isotherms can be found in Fortino *et al.* (2013). In Genoese *et al.* (2013), temperature-dependent sorption isotherms based on the Anderson-McCarthy model were also used. The isotherms are expressed in Eq. (8.36):

$$m_\alpha = -\frac{\ln\left(\ln\left(1/h\right)/f_{1\alpha}\right)}{f_{2\alpha}}; \alpha = a, d \tag{8.36}$$

where $f_{i\alpha}$ represents the shape parameters defined as functions of the current temperature T represented as polynomials $k_{i\alpha} = b_{i0\alpha} + b_{i1\alpha} T + b_{i2\alpha} T^2 + \ldots + b_{in\alpha} T^n$, $i = 1,2$. The used shape parameter $b_{ij\alpha}$ was calibrated for temperatures above zero in (Frandsen, 2007) and reported in Table 8.7.

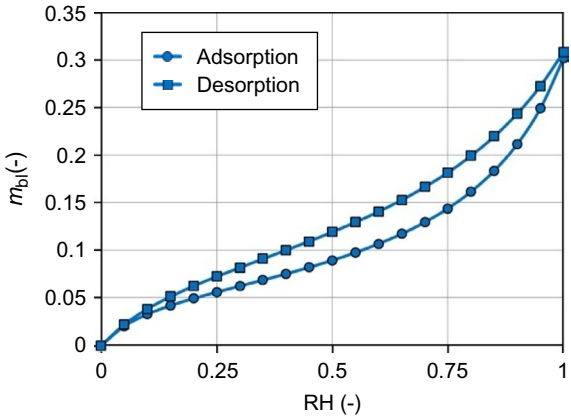


Fig. 8.5 Sorption isotherms for Norway spruce, see reference in Frandsen (2007).

Table 8.6 Parameters for the adsorption (*a*) and desorption (*d*) curves

α	$f_1\alpha$[-]	$f_2\alpha$ [-]	$f_3\alpha$ [-]
a	1.804	13.63	-12.12
d	1.886	7.884	-6.526

Table 8.7 Shape parameters for the temperature-dependent sorption function

α	$b_{10\alpha}$[-]	$b_{11\alpha}$[K^{-1}]	$b_{20\alpha}$[-]	$b_{21\alpha}$[K^{-1}]
a	11.1	–0.0234	0.0865	0.0657
d	16.3	–0.0367	2.13	0.0535

To take into account the subfreezing temperature range, the expression for saturated vapour pressure has to be changed in this range (see Fortino *et al.*, 2016). However, the assessment of a robust hysteresis model for subfreezing temperatures would require more experimental work to measure the sorption isotherms for temperatures below zero due to the lack of information in the current literature. Nevertheless, the use of two sorption isotherms rather than a range of temperature-dependent sorption curves is more useful for practical purposes since the related analysis is much simpler and faster. On the other hand, the differences between sorption curves at different temperatures were found negligible for the whole trends of numerical moisture histories calculated by multi-Fickian models (Fortino *et al.*, 2016). To simulate the hygrothermal response of wood under the effect of rain, in particular in the presence of water traps and for all cases of MC levels above the fibre saturation point, the transport of free water should be further taken into account by defining a fourth equation in the model. This topic needs future work.

8.3.4 Implementation in Abaqus code and applications

The model described in the previous section can be implemented in the subroutine Uel of Abaqus FEM code as described by Fortino *et al.* (2013) and Genoese *et al.* (2013). In particular, to obtain the discrete formulation of the problem, weak forms of Eqs. (8.28)–(8.30) are required, and the shape functions for an eight-node brick element can be used. In the work described herein, validation of the model was presented for cases of glulam beams of timber bridges and medium-size glulam specimens.

As an application, the same glulam section studied with the single-Fickian approach (Fig. 8.4, left) was analysed by Genoese *et al.* (2013) by using the multi-Fickian method with temperature-dependent hysteresis. RH and T of the air in Lisbon (airport zone) from 1.2.2007 to 25.7.2007 were used as hygrothermal loads. The moisture histories and gradients in three points located at 11.5 mm from the closest edges were studied. The results for two different levels of initial MC ($MC_0 = 12\%$ and $MC_0 = 14\%$) pointed out that the initial moisture influences mainly the first part of the solution in point A and point B marked in Fig. 8.4. On the contrary, in point C, the results for the case at $MC_0 = 14\%$ showed higher peaks. These results confirmed the importance of the exposure for wooden elements. Some differences were also found in the moisture gradients for the two cases with different MC_0. Nevertheless, for both cases, the peaks of MC and moisture gradients are reached in correspondence of the maximum value of RH (second half of Feb. 2007). However, the effect of initial MC decreases in long term so that, to have a numerical solution independent of initial MC, the results after about 6 months analysis should be considered as more realistic in a long-term calculation. In Fig. 8.6, the moisture histories in points A, B and C for the case with initial $MC_0 = 14\%$ are shown.

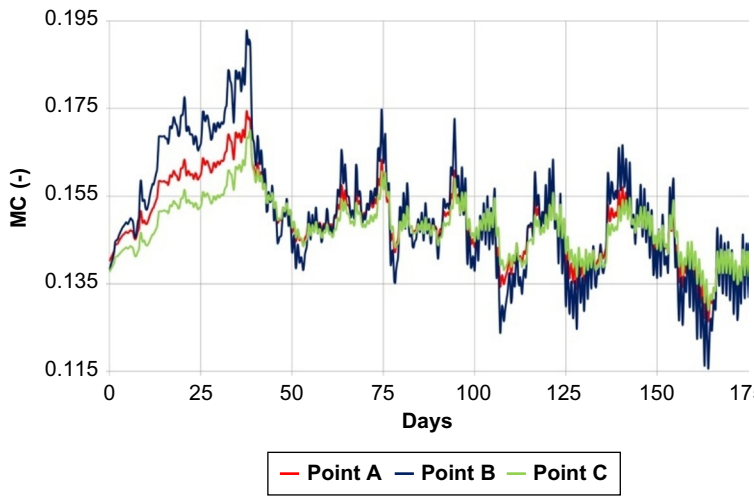


Fig. 8.6 MC during time in points A, B and C of the glulam section for $MC_0 = 14\%$ from 1 Feb. 2007 (0 days) to 25 Jul. 2007 (175 days).

8.3.5 Conclusions and future work

The described single-Fickian and multi-Fickian methods for moisture transport in wood are useful tools to simulate the moisture distribution in wooden elements of buildings. The first method is very simple to implement in FEM codes, but its accuracy could be low in cases of continuously variable climates due to the lack of internal *T* and wood sorption hysteresis. The second approach is more accurate since it describes the real phenomena happening in wood under the effects of moisture and temperature variations. In addition, also the RH and *T* inside wood are provided as results, and this can be very useful for the numerical monitoring of wooden structures. At present, the method appears particularly suitable for cases of timber elements in indoor conditions or sheltered from rain and solar radiation under outdoor climates also in the presence of temperatures below zero. However, the model should be still developed for cases of wooden elements under the effect of rain and solar radiation.

The results of the moisture analyses can be used within stress analyses aimed at evaluating moisture-induced stresses in wood. The presented hygrothermal numerical methods show a great potential to mitigate the negative life-cycle impacts caused by the moisture. This is particularly important for the assessment of durability and safety of existing timber structures. The hygrothermal methods may also lead to more sophisticated design and maintenance planning for wooden structures.

8.4 Modelling of weathering

J. Sandak[*,†], *A. Sandak*[†], *I. Burud*[‡]
*CNR-IVALSA, Trees and Timber Institute, San Michele all'Adige, Italy
[†]University of Primorska, Koper, Slovenia
[‡]Norwegian University of Life Sciences, Ås, Norway

8.4.1 Weathering as a deterioration process

Weathering is a general term used to define the slow degradation of materials exposed to climate parameters. Every material exposed to weathering is degraded by various environmental agents, and its selected properties are consequently deteriorated. An example of the progress of wood surface appearance changes when exposed to natural weathering is presented in Fig. 8.7. Various deterioration processes can be observed including alteration of colour and surface cracking. It is clear that the intensity and extent of the degradation depends on several factors, and its kinetics may vary in different bio-based materials and exposure locations.

8.4.2 Factors influencing changes to bio-based building materials due to weathering

The rate of weathering varies within one type of bio-based material, its function within a structure, architectural solutions and surface finishing technology applied but most of all on the specific local conditions and weather history. The extent of degradation

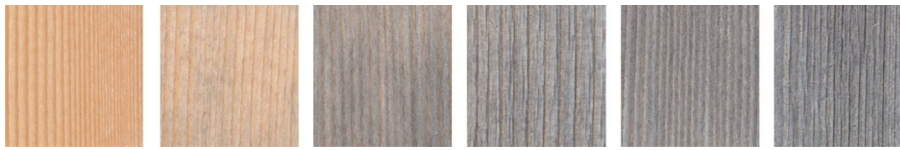


Fig. 8.7 Changes of spruce wood appearance due to natural weathering.

depends not only on the location but also on erection time of the structure and the duration of exposure (Dawson *et al.*, 2005). The most important factors affecting weathering kinetics are solar radiation and stresses imposed by cyclic wetting (moisture), together with temperature changes, environmental pollutants and actions of certain microorganisms. Unfinished raw biomaterials may weather most rapidly as a result of gradual changes to its unprotected physical/chemical structure. Nevertheless, the surface erosion rate is generally slow, being ~6 mm per century in case of typical softwood species exposed in a mild climate zone (Williams, 2005).

8.4.3 Mechanisms of surface weathering at different levels

Full understanding of the basic mechanisms, causes and effects of weathering is essential for the development of reliable and meaningful numerical models. The process of biomaterials weathering is a complex phenomenon, occurring simultaneously at various scales:

8.4.3.1 Molecular level

The absorption of UV light emitted by the sun induces lignin degradation and the photo- oxidation of functional groups (–CH_2, –CH or –OH) of constitutive polymers. The photodegradation of lignin is indicated by a rapid decrease in the lignin content accompanied by generation of carbonyl groups. Degradation of cellulose is indicated by a loss of its weight and reduced degree of polymerisation (Pandley, 2005). Tsuchikawa *et al.* (2004) reported that the degradation rates for the amorphous regions in carbohydrates were faster than in lignin. The amorphous regions in cellulose and hemicellulose and lignin are subjected to decomposition into low molecular components as a result of sunlight irradiation. On the other hand, crystalline regions of cellulose are considered as chemical structures most resistant against weathering. It has to be mentioned that hydrolysis and oxidation reactions are other significant sources of changes to biomaterial molecular structure during natural weathering (Sandak *et al.*, 2016a).

8.4.3.2 Cellular level

Chemical changes lead to a slow breakdown of surface fibres, removal and subsequent roughening of the surface and decrease of its glossiness. According to Ghosh *et al.* (2009), the greying process of weathered bio-based materials follows a particular sequence:

- Photodegradation of cell wall polymers by sunlight—especially lignin and wood extractives in the middle lamella

- Washing out degradation products by rain
- Colonisation of the surface by staining fungi able to metabolise remaining wood chemical components

Pitch cracks generated as the result of the mechanical stresses within the cell wall are caused by cycling moisture variations. Disconnection of surface cells, being an effect of the breakdown of the middle lamella, is observed early after the weathering starts (Fig. 8.8).

8.4.3.3 *Tissue level*

Early wood is more susceptible to damage due to weathering than latewood, since cells in early wood have thinner/weaker cell walls and relatively high porosity. Surface cracks on the radial section occur primarily at the annual ring border due to abrupt change of the density in the transition zone (Sandberg, 1999). Early wood erodes more quickly than latewood, and measurable attrition can be noticed already after a few weeks of exposure (Fig. 8.9).

8.4.3.4 *Macro level*

Changes of the visual appearance, including colour, roughness, surface checking, dirt uptake and growth of mould, are the most apparent effects of biomaterial weathering (Pfeffer *et al.*, 2012). Dramatic changes to the surface colour occur already after a few months of exposure (Fig. 8.7). The surface became gradually grey up to the moment

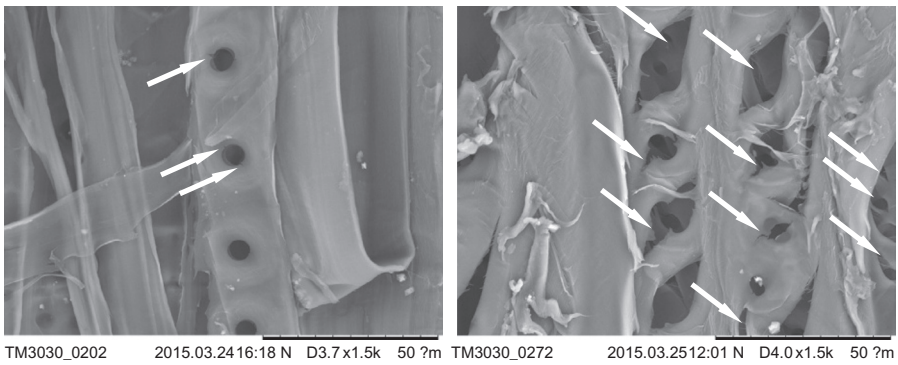


Fig. 8.8 Scanning electron microscope images of spruce wood exposed to natural weathering for 7 (A) and 24 (B) days. Note, arrows indicate points of the pitch cracks.

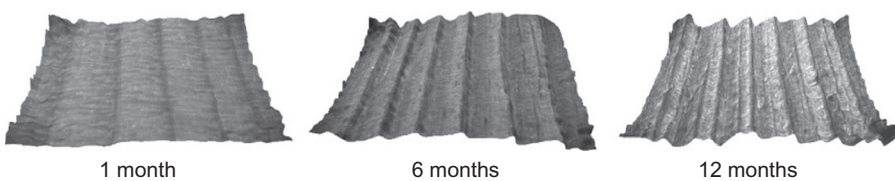


Fig. 8.9 Surface erosion of wood surface exposed to natural weathering for 1, 6 and 12 months.

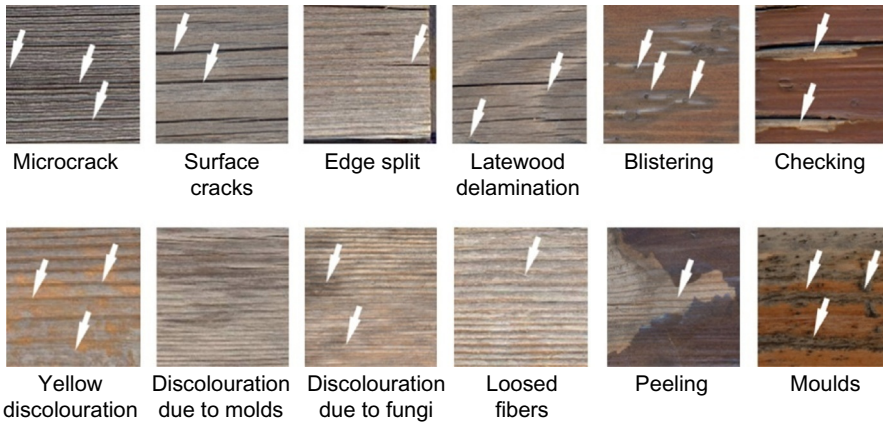


Fig. 8.10 Defects occurring on natural and coated wood surfaces due to weathering.

when mould or fungi further alter the colour. In most cases, the surface gloss decreases with the progress of surface weathering, but it is highly affected by the surface roughness increasing monotonously along the weathering time. Several surface defects may appear on untreated and coated surfaces of biomaterials as shown in Fig. 8.10.

8.4.4 Preparation of reference data for models

Development of high-quality numerical models requires access to an extensive data set of reference information containing a wide range of weathering scenarios. A list of suitable sensors/techniques that can be adopted for characterisation of weathered bio-based materials is summarised in Table 8.8. A variety of information can be gathered by each sensor, even though it does not provide a complete characterisation of all properties of interest.

Multisensor assessment is an interesting alternative, although the efficient fusion of data from different sources of information is a great challenge. Data collected from diverse instruments are often based on dissimilar foundations and reflect varying material properties. Although clear variation between suitable sensors is evident (in terms of measurement principle, sensitivity, reliability, measurement cost and time), the common feature is that each sensing technique provides some particular signals. Some sensors may be more accurate than others, depending in each case on the specific application conditions. Finally, the data collected from different sensors are usually correlated with each other, which make it necessary to interpret these together (Sandak *et al.*, 2016b). In most cases, raw data acquired by sensors are not suitable for direct interpretation and even more for multisensor data fusion. Therefore, preprocessing of raw signals is a routine task usually performed before any further data evaluation. Several treatments are available, including

- electronic signal conditioning—amplification, filtering, compensation, etc.;
- numeric signal manipulation—normalisation, filtering, correction, derivative, integration, noise reduction, smoothing, interpolation, averaging, convolution, etc.;
- digital signal processing—compression, filtering, wavelet analysis, Fourier transform, etc.

Table 8.8 Non-destructive sensing techniques usable for characterisation of weathered wood

	Aesthetics				Surface property		
Sensor	*Colour*	*Pattern*	*Gloss*	*Roughness*	*Chemistry*	*Moisture*	*Pollutions*
Colorimeter	✓						
Gloss metre			✓	✓			
Stylus				✓			
Laser displ. sensor				✓			
VIS spectrometer	✓						
NIR spectrometer					✓	✓	✓
Moisture metre						✓	
CCD camera	✓	✓		✓			
Hyperspectral camera	✓	✓			✓	✓	
IR camera		✓				✓	
XRF spectrometer							✓

The optimal selection of signal preprocessing is crucial for the overall performance of the multisensor system and for the presentation of results (Sandak *et al.*, 2015a).

The usual result of the data fusion process is a matrix containing series of parameters corresponding to single sample/case, collected at a given moment or over a defined period of time. The size of the spreadsheet may vary depending on the complexity of the system, the number of sensors utilised, the quantity of samples/cases and the duration of the test. In general, the more complex (in terms of the number of variables and samples) the collection of fused data, the more reliable/generalised numerical models may be created (Sandak *et al.*, 2015a).

8.4.5 Estimation of the weathering extent

The quantitative description of the surface degradation progress along the weathering duration is a required step for the numerical model development. The concept for calculation of weathering coefficient was previously presented by Sandak *et al.* (2015b). The custom algorithm for multisensory data fusion and computation of a weathering indicator normalises the raw data (parameters) p_i as obtained by each sensor i and summarises these, considering their importance (weight) w_i. The W_{ind} computation algorithm is mathematically expressed in Eq. (8.37):

$$W_{ind} = \frac{\sum w_i \cdot p_i}{\sum w_i} \tag{8.37}$$

The resulting W_{ind} can be considered as a weighted average indicating the state of the surface degradation, where $W_{ind}=0$ corresponds to a non-weathered sample and $W_{ind}=1$ to its terminal state. The weathering indicator method is a simple technique usable to combine information from various sources. Nevertheless, it is frequently applied to directly model the effect of the weather on a single property, such as *CIE L*a*b** colour change (ΔE), surface corrosion, glossiness or surface free energy.

8.4.6 Determination of the weather dose

Brischke and Thelandersson (2014) reviewed available modelling approaches for predicting performance of wood products outdoors and concluded that dose-response models seem to be most frequently applied. In this approach, the changes in any material property are related to the dosage of the relevant environmental factors.

The ambient moisture conditions, temperature and solar irradiance have a large influence on the degradation of biomaterials. The 'sum of total Joules' as the time-related dose indicator was proposed by Grossman (1994) for the calculation of the amount of radiation that the sample has been exposed to. This is obtained by integrating the solar energy over the entire spectra and multiplying by exposure duration (Smeland *et al.*, 2016). The consistency of the weather dose parameter can be improved by considering also other factors, such as surface temperature, moisture within bulked biomaterial and relative humidity of the surrounding air. Simulation methodology for determination of the weather dose of the building façade was reported by Thiis *et al.* (2016). It is important to mention that the surface temperature can be very different than the ambient air temperature, especially when the building elevation is exposed to the direct sunlight. Nevertheless, both solar radiation and wind-driven rain are assumed to be the two main driving factors influencing kinetics of changes to the biomaterial appearance in service (Rüther and Time, 2016).

The weather dose computation requires source data. These can be obtained from specific databases or specialised services. Data formats commonly encountered in climate research fall into three generic categories: gridded binary (*GRIB*), network Common Data Form (*netCDF*) and hierarchical data format (*HDF*). All of these formats are portable and self-describing. However, the most appreciated are the weather data acquired at the testing site by means of a dedicated weather station. The optimal time resolution and sampling frequency of data depend on the modelling approach and objective of evaluation. In most cases, it may vary between 5 min and 30 days.

8.4.7 Methods for numerical modelling of weathering

Several approaches to model performance of timber structures during their service life have been proposed by various authors. The first attempt to correlate climatic data with the hazard for decay was presented by Scheffer (1971) as a climate index. Numerous research projects were focused on predicting functional service life and performance of timber components with respect to the range of degrading factors. Most of these were based on numerical models, predicting wood decay (in or above ground), attack by termites

and marine borers. As a consequence, diverse experimental approaches and concepts of modelling were implemented (Brischke *et al.*, 2011; Van de Kuilen, 2007; Viitanen *et al.*, 2008). The so-called factor method is currently considered the most commonly used, and it is implemented within the service life planning methodology according to ISO 15686-1 (ISO, 2011). Other unconventional techniques are briefly presented below.

8.4.7.1 Regression models

The deterioration progress due to weathering can be modelled by means of an algorithm based on the partial least squared (*PLS*) regression and considering the whole set of cases representing diverse situations. The procedure for determination of the weathering indicator W_{ind}^{PLS} is schematically described in Fig. 8.11. In principle, the simple PLS regression model is established on the base of two extreme samples: not exposed and at the final stage of the weathering deterioration. The reference values of the degradation index are defined there as $W_{ind}^{PLS} = 100$ and $W_{ind}^{PLS} = 1000$ respectively. This PLS model is then applied to predict the degradation indexes W_{ind}^{PLS} for all the other cases allowing direct analysis and scenario comparisons (Sandak *et al.*, 2016a).

8.4.7.2 Dose-response models

The PLS modelling of weathering described above is an efficient method to quantify the progress of the degradation. However, it does not automatically relate degradation with the climate history. Various weather factors may cause different extents of material alterations. In consequence, dose-response relationships can explain the degradation of a material as a function of varying exposure conditions. The scheme of this concept is presented in Fig. 8.12, where series of corresponding weather data are processed in order to calculate the weather index (dose). In parallel, the quantification of the material degradation (responses) is determined by means of a weathering indicator W_{ind}^{DR}, where *DR* stands for dose-response. Ultimately, the numerical relationship between the material state W_{ind}^{DR} and a certain exposure condition is generated by using any suitable algorithm, including machine learning or statistical regression. Such a model can later be used to simulate the degradation progress for new cases and to predict the weathering index for a given climatic exposure.

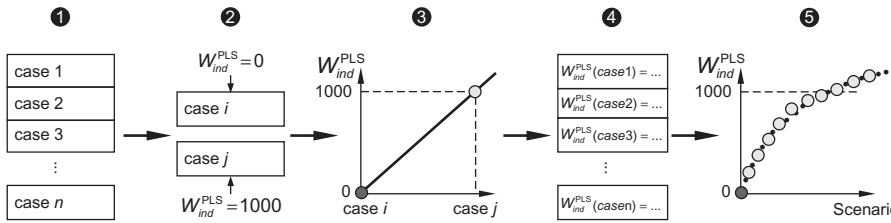


Fig. 8.11 Modelling of weathering with partial least square approach ❶—collection *n* sets of data corresponding to different cases, ❷—selection of two reference cases representing initial stage of weathering and a reference state, ❸—development of PLS model on the base of two reference points, ❹—apply PLS model for prediction of the weathering indicators for all cases from the collection and ❺—data mining and prediction of the weathering indicators.

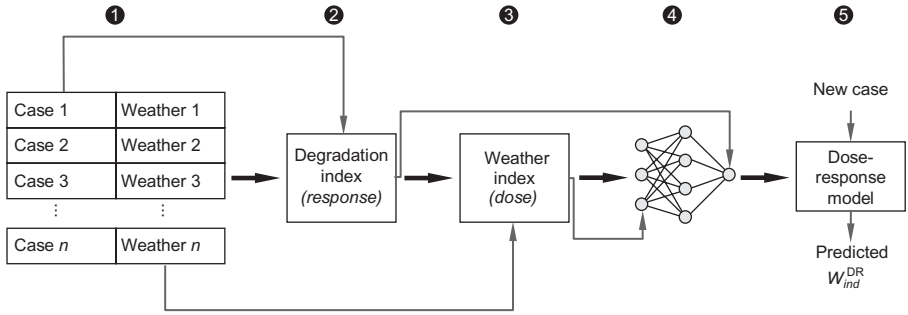


Fig. 8.12 Modelling of weathering with dose-response approach ❶—collection of *n* sets of data corresponding to different cases including meteorological records, ❷—computation of the degradation index as a system response, ❸—computation of the weather dose, ❹—application iterative numerical modelling algorithm for prediction of the degradation index on the base of the weather dose and ❺—use of dose-response model to predict the weathering indicator for any case sample.

8.4.7.3 Multi-way approach for modelling

Multiway data analysis (*MWA*) is a method of analysing large data sets by representing the data as a multidimensional array. In this method, several dimensions represented in the data set may be measured at various times, in different places or using diverse methodologies. Multiway methods are particularly useful for time series analysis (time-variable-lag), and for that reason, it seems to be a perfect tool for application of weathering modelling. The concept of MWA is presented in Fig. 8.13, where series of variables are acquired for each experimented case along the weathering duration. For computational reasons, proper unfolding of the data is essential: the multiway array of data must be rearranged into a matrix. A set of loadings and scores for each mode, case and variable is provided as a result of MWA. Loadings can then be analysed separately providing new interpretation of the influences of investigated experimental variables (e.g. exposure duration, test location, altitude and surface finishing). The model can also be applied to simulate the weathering progress W_{ind}^{MV} for any new cases or weathering scenarios.

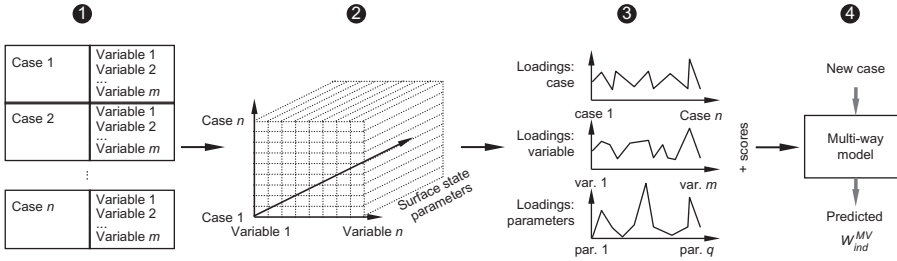


Fig. 8.13 Modelling of weathering with multiway approach, ❶—collection series of corresponding data sets, ❷—unfolding data, ❸—development of multiway model including loadings and scores and ❹—apply multiway model for prediction of the weathering indicator for unknown case.

8.4.8 Weathering models validation

Validation procedure confirms the exactness of the model's representation of the real systems and assures its high credibility. In the optimal case, models should be robust and general enough to properly explain the variability not only within the data used for the model development but also in any other case, not necessarily included in the teaching data set. Diverse model validation strategies are recommended depending on the extent of the available cases and on the future accessibility to new independent data. Nevertheless, external validation with independent data is always considered as an optimal solution and therefore recommended for routine implementation.

Moreover, a very important task is to assure a continuous upgrade of the numerical models. Whenever possible, the software system should automatically acquire new knowledge along the service time and incorporate it with the original model.

8.5 Decay models

C. Brischke[*,†], *H. Viitanen*[‡,§]
*Leibniz University Hannover, Hannover, Germany
[†]University of Göttingen, Göttingen, Germany
[‡]Aalto University (Docent), Espoo, Finland
[§]VTT Technical Research Centre of Finland Ltd, Espoo, Finland (Senior Research Scientist; Emeritus)

8.5.1 Model types

Predicting the performance of bio-based building materials requires modelling onset and development of fungal decay and other types of biotic degradation. The mathematical background for any performance prediction is therefore a performance model.

Mathematical models are widely used in natural sciences to handle different variables, such as input variables, state variables, exogenous variables, random variables and output variables. Depending on the system to be analysed, the type and structure of the most suitable model might significantly differ and so do the preferences of scientists such as biologists, physicists, material scientists, engineers and architects. Engineering models frequently work with limit states (limit state design, *LSD*), and therefore, the limit state theory is already established in numerous building codes around the world (see Section 8.6).

In contrast, biological models tend to display full life cycles or degradation processes, respectively. This stands to some extent in contrast to the limit state concept if it is not regarding the full life span of a building component.

Alternatively, dose-response functions can be used to describe the change in effect on an organism caused by differing levels of exposition (= dosage) to a stressor after a certain exposure time. Biodegradation of bio-based building materials can be

understood as a negative growth process—the (positive) growth of and degradation by decay organisms causes a reduction of strength and biomass, with consequences for serviceability and safety against failure. The principle of a dose-response relationship is displayed in Fig. 8.14. The typical sigmoid graph represents the full life span of bio-based building component starting slowly with an initial lag phase before onset of decay (e.g. limit state 1) and finally ending with an approximation to complete failure (here, limit state 4).

This mathematical model neither is based on linear functions nor does it provide one exclusive limit state, which might apparently conflict with the ideal preconditions of an engineering approach. But it is the opposite: besides the fact that the description of growth processes through logistic functions is definitely the more precise way, the approach even provides to define more than one limit state. Thus, purpose of specific limit states can be defined, e.g. the onset of mould or decay to define aesthetic service lives or the failure in building damage or in-ground contact as one might prefer to use for fence and utility posts. Each limit state can be related to a certain critical dose D_{crit}, which is obtained by accumulating dosage in certain time intervals such as days, months or years. The dose-response approach does also allow factorisation and normalisation of the different impact variables affecting service life of structures or components and can therefore be implemented in engineering tools. The dose serves as an input variable, which can be a dimensionless measure and is a function of exposure-related parameters such as moisture content (MC) and/or temperature (T).

The dose-response relationship shown in Fig. 8.14 might be considered as an ideal or normal scenario. Nevertheless, degradation processes and thus performance of building

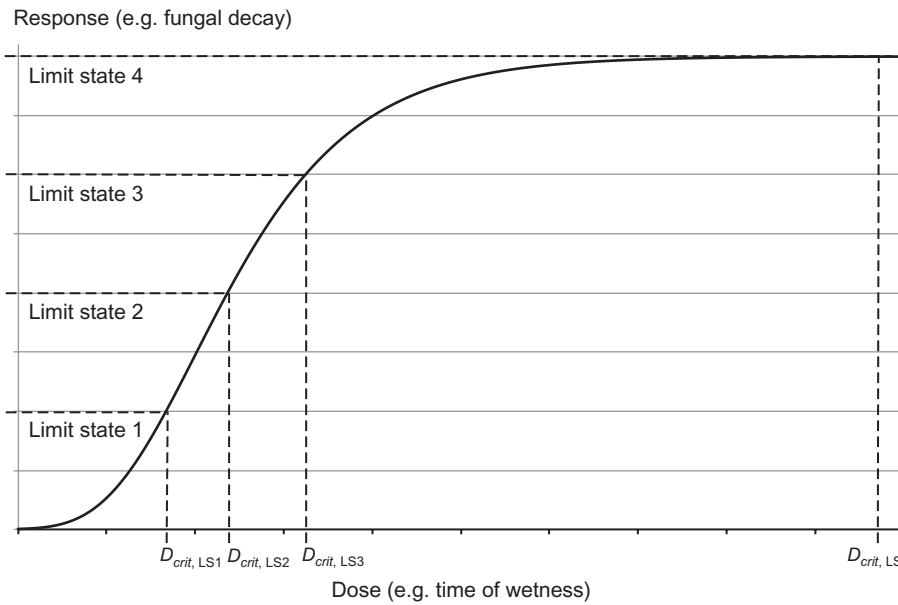


Fig. 8.14 Graphical illustration of a dose-response model.

components over time can significantly deviate from this normal case depending on the material, the degrading agents, the component dimension and design and many other factors. Larsson-Brelid *et al.* (2011) showed examples of different decay progress patterns for untreated and differently preservative-treated wood exposed in ground contact. Untreated and non-durable softwoods decayed almost immediately after exposure to suitable conditions for decay to develop or to soil and followed a linear degradation course over time. In contrast, most of the preservative-treated materials showed time lags between exposure and onset of decay. Wood impregnated with creosote showed also 'break phases' after decay had already started, when degradation seemed to be interrupted for several years before it continued again. Similar observations had been reported for natural durable timber species by Brischke *et al.* (2009) and Stirling *et al.* (2016).

Such 'irregularities' must not be ignored to avoid overestimating or underestimating the performance of a material from extrapolation of decay data from first phases of life.

Computer programmes would be eligible for performance prediction into which users enter information, and the system utilises preprogrammed logic to return output to the user. The 'black-box' portion of such systems contains formulas and calculations that the user does not see and does not need to know to use the system. Especially for biological processes, this may cause problems, for example, when dealing with material or decay type-specific mechanisms (e.g. Larsson-Brelid *et al.*, 2011; Brischke and Meyer-Veltrup, 2015). The more transparency is provided by the model, i.e. the more the model is a 'white box', the less prominent is the risk of misinterpretation and erroneous prediction.

An ideal tool to predict decay should therefore be based on a completely transparent model (= white box) with traceable functional relationships to allow continual adjustment and considering more and more input data. As manifold data sources need to be tapped, the model approach needs to be 'open'—open for lab and field test data, moisture recordings from in-service components, commodity tests, surveys and questioning results, case studies, expert and non-expert opinion and results from complementary studies. The model should also allow defining different limit states and different types of 'target performance' and recalibration on the base of short-term, long-term and real-life *in situ* tests. It needs to be linked to exposure models and resistance models reflecting the impact of the exterior environment and the material-intrinsic protective properties, respectively.

8.5.2 Modelling approaches and applications

8.5.2.1 Climate indices

As mentioned in Section 8.4.7, pioneering work on performance prediction was done by Theodore Scheffer in the early 1970s. Scheffer (1971) correlated the climatic parameter temperature and rainfall distribution with the empirically determined decay intensity from field tests at four different sites in the United States. The site-specific potential for decay in above-ground exposures is expressed as follows in Eq. (8.38):

$$\text{Scheffer climate index } SCI = \frac{\sum_{Dec}^{Jan}\left[(T-35)(D-3)\right]}{30} \tag{8.38}$$

where

T = mean day temperature of the month (°F)
D = *mean number of days with more than 0.001 inch of rain per month (-)*

The hazard for decay of wood increases with the value of the index, which ranges from 0.0 for Yuma, Arizona, to 137.5 for West Palm Beach, Florida, for the continental part of the United States, where three climate zones represent three levels of above-ground decay potential. Originally, the index was developed to estimate the decay potential of sites in the continental part of the United States; later on, it had also been applied to other parts of the world, e.g. Canada (Setliff, 1986), North America (Morris and Wang, 2008), China (Wang *et al.*, 2007), Japan (Hasegawa, 1996), Australia (Francis and Norton, 2006; Wang *et al.*, 2008), Norway (Lisø *et al.*, 2006), Scandinavia (Niklewski *et al.*, 2016b), Turkey (Köse *et al.*, 2013) and Europe (Brischke *et al.*, 2011).

According to Carll (2009), the Scheffer index is a 'metric by which relative hazard can be compared between geographic locations, the Scheffer index is not intended to predict decay propagation rate nor time to failure in specific constructions'. This peculiarity is not necessarily a limitation of the approach, but has been controversially discussed in numerous reports (e.g. De Groot, 1982; Norén, 2001; Brischke *et al.*, 2006; Larkin and Laks, 2008; Carll, 2009; Morris and Wang, 2011). Nevertheless, without doubt, the Scheffer index is still the most frequently used index of its kind for estimating the relative decay hazard of geographical sites.

Further climate indices have been developed and considered for service life prediction (e.g. Beesley *et al.*, 1983; Creemers *et al.*, 2002; Cornick *et al.*, 2003; Grinda and Carey, 2004; Morris and Wang, 2011). However, one may conclude that many previous attempts to correlate macroclimatic data with decay rates lacked sufficient fit, because more influences on wood decay need consideration such as the microclimate provoked by details in design (Brischke *et al.*, 2006; Lebow and Highley, 2008; Thelandersson *et al.*, 2011).

The paramount importance of climate indices for service life prediction and performance-based design evolves from several aspects: firstly, the local climate is directly influencing the material climate and thus the conditions for growth and decay of wood-destroying fungi in constructions exposed to weather. Secondly, climate parameters are important input variables for prediction models that can nowadays easily be accessed for almost every spot on earth. Thirdly, 'climate' is something easy to reach for everyone in the design process, that is, architects, engineers, planners, builders, craftsmen and users. Finally, climate is almost unchangeable by individuals, but a sensitive set screw affected by humankind. The potential effect of climate changes on durability of wood and thus on the longevity of timber structures is evident (Brischke and Rapp, 2011) but hard to predict in a quantitative and accurate manner (Fig. 8.15).

8.5.2.2 *Exposure, decay, and resistance models*

Performance prediction of wooden structures is generally a three-step approach (Brischke and Thelandersson, 2014; Brischke *et al.*, 2015; Niklewski *et al.*, 2016a,b). As illustrated in Fig. 8.15, a design solution is considered successful if the exposure dose over time (here, $d(t)$) stays equal or below a critical dose d_{crit} characterising the

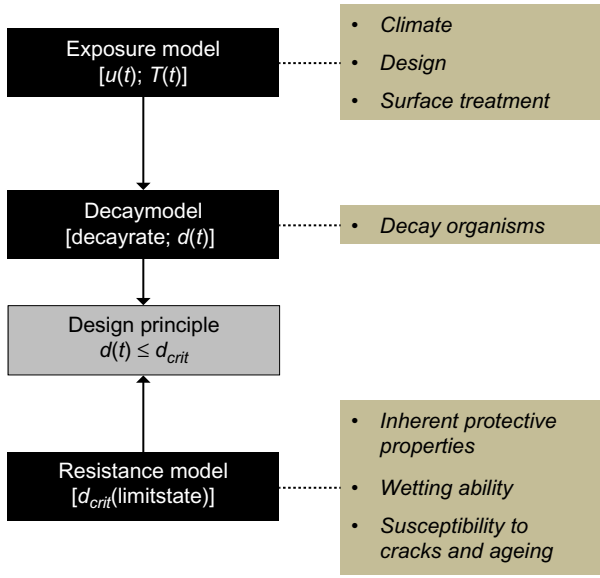


Fig. 8.15 Performance-based design concept; where u = wood moisture content, T = wood temperature, t = exposure time, d = dose and d_{crit} = critical dose (Brischke *et al.*, 2015; Niklewski *et al.*, 2016a).

resistance of the material in use. In other words and in analogy to structural engineering, the load should never exceed the capacity.

To quantify the dose on 'both sides of the balance', at least three separate models are needed:

Resistance models

A resistance model should allow for quantifying the resistance of a material against the various deteriorating agents based on the material inherent protective properties, wetting ability and susceptibility to crack formation and ageing. A first attempt to utilise laboratory and field test data to predict the material resistance of a variety of naturally durable wood species on the base of a dose-response concept has been made by Meyer-Veltrup *et al.* (2017).

Decay models

The input variables for decay models are material climatic parameters such as ambient humidity, wood moisture content and temperature. Viitanen (1997) developed a decay model of brown-rot fungi that cause damage in building components. The model is based on the effect of ambient humidity (RH), moisture content of wood, temperature (T) and exposure time (t). The aim of the model is to evaluate the decay risk in different structures exposed to elevated humidity exposure. He also studied the effect of drying on the survival of brown-rot fungi for evaluation of drying effect on the decay capacity (Viitanen, 1994).

The decay model was later developed to be used for evaluation of climatic exposure conditions and decay development in the wood surface (Viitanen *et al.*, 2010a). The overall aim of a decay model is to predict the time to onset of decay and the progress of fungal degradation from the variation of the material climate over time. Dose-response relationships have frequently been established to predict either service lives or decay rates, respectively. Different limit states can be defined to determine the critical dose d_{crit} such as 'onset of decay', 'failure' or a certain mass loss percentage (Thelandersson *et al.*, 2011; Viitanen *et al.*, 2010a).

Alternatively, factorisation approaches were developed following the factor method as described in ISO 15686-1 (ISO (2011)). One of the first and most comprehensive attempts to model decay and other damage of wood have been made within the Australian 'TimberLife' project (MacKenzie *et al.*, 2007). Besides others, a basic model for timber decay above ground was established on the basis of field test results and is expressed as decay depth over time (Wang *et al.*, 2008). The rate of decay is hereby considered as the product of different factors according to the Eq. (8.39):

$$r = k_{wood} k_{climate} k_p k_t k_w k_n k_g \tag{8.39}$$

where

r = decay rate
k_{wood} = wood parameter
$k_{climate}$ = climate parameter
k_p = paint parameter
k_t = thickness parameter
k_w = width parameter
k_n = fastener parameter
k_g = geometry parameter

Furthermore, a time lag (before onset of decay) was determined according to Eq. (8.40):

$$\text{time lag } t_{lag} = 8.5 r^{-0.85} \tag{8.40}$$

Algorithms for the different k-factors were provided in CSIRO Manual No. 4 by Wang *et al.* (2008).

Exposure models

The final step in performance modelling is to predict the material climate within a wooden component from external factors such as climate, design and potential surface treatments (e.g. Niklewski *et al.*, 2016a,b). Numerous attempts have been made to derive wood moisture content and temperature from local climate under consideration of the respective design solution (e.g. Creemers *et al.*, 2002; Häglund, 2007; Fortino *et al.*, 2013; Isaksson and Thelandersson, 2013; Fredriksson *et al.*, 2013, 2014).

Whilst the majority of exposure models describe the diffusion processes in wood in the hygroscopic range, the more crucial way of moistening wood exposed outdoors

is the capillary uptake of liquid water, for example, due to rain or condensation. More recent approaches aim on combining the two principal ways of wetting, diffusion and capillary condensation and water vapour desorption during redrying (e.g. Frühwald Hansson *et al.*, 2012, Niklewski *et al.*, 2016a,b).

Linking the three general steps of modelling—usually represented by at least three different (sets of) models— is the final challenge and requires a lot of adjustment with respect to the variety of different design solutions, materials and ways to modify and preserve the latter and local climate divergences, e.g. due to topographic peculiarities of a location.

The mould and decay models can be connected to hygrothermal models like WUFI simulation for evaluating the potential risk of mould and decay to develop. Viitanen *et al.* (2008, 2010) presented reports on the use of models in simulations (see also Section 8.3). A more comprehensive overview on existing approaches for modelling the outdoor performance of wood has been given by Brischke and Thelandersson (2014).

8.5.3 Application of models

8.5.3.1 Hazard mapping

Climate indices help in serving as both starting point for decay prediction and final outcome of advanced performance modelling (Morris and Wang, 2008; Viitanen *et al.*, 2010a,b; Niklewski *et al.*, 2016a,b) that can furthermore be illustrated in hazard maps. The first of its kind was the Scheffer climate index (SCI) (Scheffer, 1971), which is still frequently used to estimate the climate-induced potential for fungal decay and for the interpretation of field test results. More recently, the SCI was calculated and mapped on the basis of Meteonorm climate data for Europe (Brischke *et al.*, 2011).

Viitanen *et al.* (2010a,b) developed a decay risk model based on previous laboratory test data and further utilised it to estimate wood decay at different locations in Europe. Therefore, the model was applied to ERA-40 reanalysis data using 6 h weather observations in Europe. Based on the weather parameters RH, temperature and precipitation, the mass loss of Scots pine sapwood caused by brown-rot fungi was modelled for wood exposed to rain and for wood protected from rain (Fig. 8.16). The latter was calculated based on RH and temperature data only; in case of rain events, the RH was set to 100% (at non-freezing temperatures), which means that no capillary uptake of liquid water was allowed by the model.

With respect to the absolute values of estimated mass loss, the model appeared to be conservative at least for sheltered wood. As shown in Fig. 8.16, Scots pine sapwood was expected to show more than 20% mass loss by brown rot after 10 years. When wood is protected from rain—and provided there is no external moisture source—less mass loss shall be expected from a biological viewpoint since the presence of liquid water inside wood is an essential requirement for its degradability by fungi (e.g. Schmidt, 2006; Wang *et al.*, 2008; Meyer and Brischke, 2015).

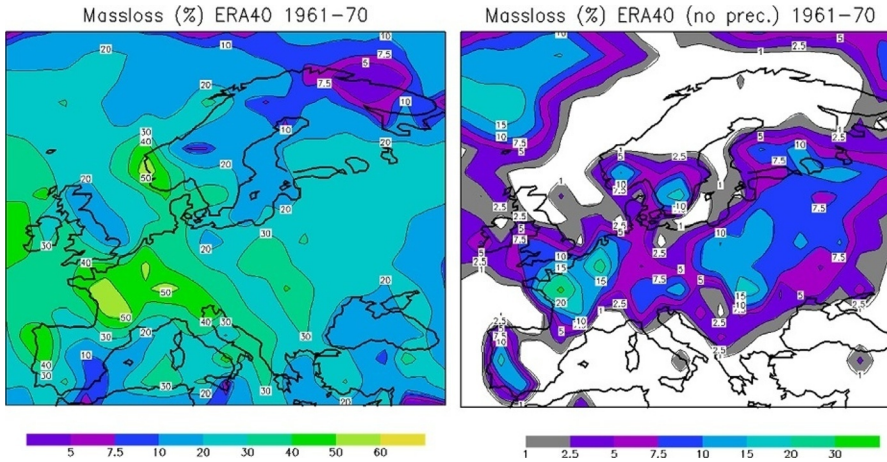


Fig. 8.16 Modelled mass loss (in %) of small pieces of pine sapwood after 10 years in Europe. Left, exposed to rain. Right, protected from rain (Viitanen *et al.*, 2010a,b).

The performance model developed by Brischke and Rapp (2010) has been utilised for a dosimeter-based decay hazard map by Niklewski *et al.* (2016b). Therefore, an additional 'exposure model' has been developed that described the relationship between the weather parameters RH, temperature and precipitation on the one hand and the material climatic parameters wood moisture content and wood temperature on the other hand (Niklewski *et al.*, 2016b). For the decay hazard mapping, the decay risk at 302 sites in 38 European countries was calculated and related to the decay risk (annual dose) of Uppsala in Sweden. A decay hazard above 1 means higher decay potential compared with Uppsala; a number below 1 means lower decay potential than in Uppsala. Isopleths of the same decay hazard have been calculated by interpolation using splines as shown in Fig. 8.17.

8.5.3.2 Service life prediction and design guidance

Service life prediction and planning is an essential element of performance-based building *PBB* (Thelandersson *et al.*, 2011; Isaksson *et al.*, 2013). Therefore, models were sought enabling service life estimates for buildings or building components, whereby the focus was not always on determining discrete numbers of years. Performance indicators or relative measures (related to reference products with a reference service life) were often the more appropriate measure to work with in design. Exposure to water and high humidity is the main reason for damage in building and building components (Viitanen and Salonvaara, 2001; Viitanen *et al.*, 2010a,b). Details are often the most important factor for prevention of decay.

A principal methodology for service life planning is given in the ISO 15686 standard series with the 'factor method' as a key element (ISO, 15686-1, ISO, 2011). The method is named according to the calculation of an estimated service life (*ESL*)

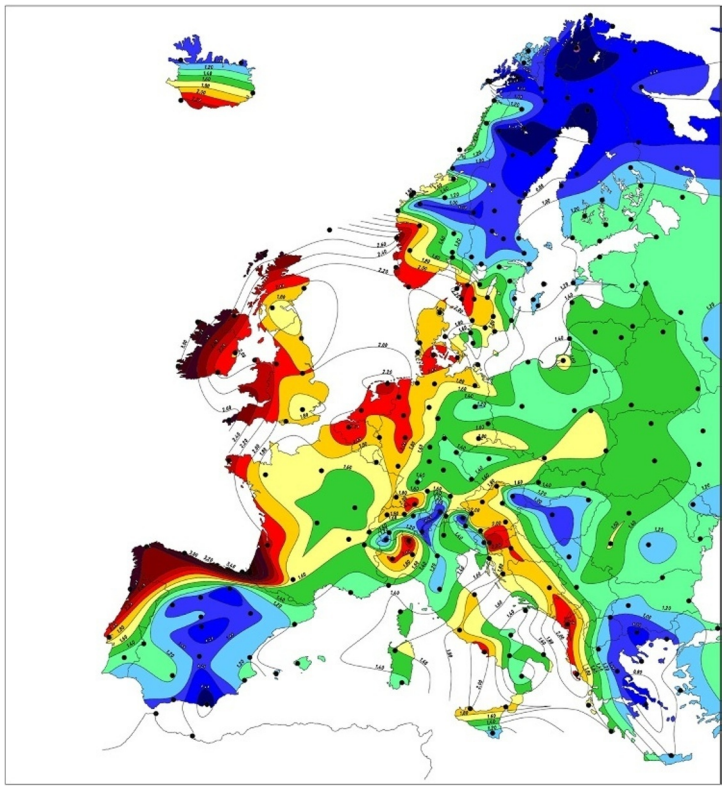


Fig. 8.17 Relative decay potential for Europe indicated as relative dose according to an empirical exposure model and a logistic model for fungal decay of wood for 302 European sites *(black dots)* based on data from Meteonorm (normal years) (Niklewski *et al.*, 2016b).

by multiplication of a reference service life (*RSL*) with different modifying factors, which consider the deviation of influences from reference conditions as shown in Eq. (8.41):

$$\mathrm{ESL} = \mathrm{RSL} \times A \times B \times C \times D \times E \times F \times G \tag{8.41}$$

where

ESL = estimated service life
RSL = reference service life
A–*G* = modifying factors for each of the following: *A* is quality of components, *B* is design level, *C* is work execution level, *D* is indoor environment, *E* is outdoor environment, *F* is in-use conditions and *G* is maintenance level.

Multiplying the various factors induces a high risk of error propagation and therefore may be seen as a drawback, and numerous modifications of the factor method have been suggested (e.g. Abu-Tair *et al.*, 2002; Dickinson, 2005; Thelandersson *et al.*, 2011). Nevertheless, the idea of considering the full spectrum of potential

impact factors is beyond controversy and can be reflected by a more general formulation of the factor method as follows in Eq. (8.42):

$$\mathrm{ESL} = f\left(\mathrm{RSL}, A, B, C, D, E, F, G\right) \tag{8.42}$$

Various performance models have been applied for service life prediction on practical examples and building components. For instance, the logistic decay model by Brischke and Rapp (2010) has been used to estimate service lives of wooden claddings with different eaves and compass orientations, fence elements and terrace decking (Brischke *et al.*, 2010, 2013a,b). Further experimental studies with continuous MC recordings on different design and construction details have been conducted by Isaksson and Thelandersson (2013). They estimated the behaviour (in terms of performance) of an arbitrary detail by scaling the behaviour of a reference detail up or down using a constant value. The effect of different joints and other design details on the moisture performance of timber elements has been examined by Fredriksson *et al.* (2013, 2014).

Within the European WoodWisdom-Net project 'WoodExter', a first technical guideline for design of wooden constructions with respect to durability was developed and later on improved and verified on the base of long-term moisture and climate observations from the Swedish research programme 'WoodBuild' (Thelandersson *et al.*, 2011; Isaksson *et al.*, 2014). On an engineering level, the design condition is then formulated as shown in Eq. (8.43):

$$I_{Sd} = I_{Sk}\gamma_d \leq I_{Rd} \tag{8.43}$$

where

I_{Sk} = characteristic exposure index
I_{Rd} = design resistance index
γ_d = factor accounting for consequence of violating the limit state

In analogy to the principles of ISO 13823 (ISO (2008)), the design is accepted if the condition in Eq. (8.43) is fulfilled; otherwise, it is not accepted. The exposure index I_{Sk} is determined by Eq. (8.44):

$$I_{Sk} = k_{s1} \cdot k_{s2} \cdot k_{s3} \cdot k_{s4} \cdot I_{S0} \cdot c_a \tag{8.44}$$

where

I_{S0} = basic exposure index depending on geographical location/global climate
k_{s1} = factor describing the effect of local climate conditions (mesoclimate)
k_{s2} = factor describing the effect of sheltering
k_{s3} = factor describing the effect of distance from ground
k_{s4} = factor describing the effect of detailed design
c_a = calibration factor to be determined by reality checks and expert estimates

The WoodExter/WoodBuild approach is consequently closely following the factor method idea according to ISO 15686-1 (ISO (2011)) but is at the same time an engineering approach with clearly defined limit states and can be fed by dose-response models.

Finally, the above-mentioned 'TimberLife' project is considered to be the most comprehensive attempt to utilise performance models regarding biological degradation of timber structures for design guidance and has been published in a number of CSIRO manuals in Australia.

8.5.4 Challenges

8.5.4.1 Data for modelling

The fundament of any model is data. Performance models require performance data, which are often not easily accessible or hard to interpret. The quality of a prediction model depends consequently on the quality of available data to develop and—at least of the same importance—to verify the model.

Performance and service life data for wood-based building materials can be found less frequently than one should expect when looking back on decades of wood and wood protection research. Even worse is the situation for non-wood bio-based building products. The reasons for the lack of high-quality data are manifold: first of all, it is hardly affordable to monitor buildings over their entire lifetime. The more durable a material, the smaller is the number of service life records. Secondly, testing procedures aim on obtaining results within a short-to-medium time span. Hence, even field tests do not usually last longer than five years, which is only a fraction of the lifetime of for instance a timber construction or a thatched roof to be expected. The test conditions, however, are really higher than those under normal use conditions, and the tests conditions refer to the damage situations. The majority of field test durability data derives from in-ground tests and transfer to above-ground situations is a challenging task. Thirdly, test data and results from surveys are usually not available as raw data. Those either stay unpublished or become codified, for example, in terms of wood durability classes (*DC*) (EN 252 (CEN, 2015); EN 350 (CEN, 2016)) and thus almost useless for service life modelling.

A modern way of collecting, storing and providing performance data is the installation of web databases (e.g. Daniotti *et al.*, 2010; Nambu and Ikaga, 2011). Although several databases are related to *LCA* and *LCC* of building products including bio-based products, they necessarily do contain neither service life and durability data nor test data in a processible raw format. Laboratory and field tests have been performed around the world for many decades with a huge variety of bio-based materials, but unfortunately, most of the data are not available in a form that can be utilised for service life models.

In response to this challenge, an initiative has been taken within the framework of the International Research Group on Wood Protection (*IRG-WP*). The IRG-WP durability database (http://www.irg-wp.com/durability/index.html) aims to improve the usability of existing performance data and create added value for durability research and service life prediction (Brischke *et al.*, 2012). The database went live in 2013 and as of April 2017 has received 248 submissions from 14 different countries.

8.5.4.2 Dealing with variability

Variability is crucial for performance modelling in many aspects. Results from durability tests and outcomes from surveys that both can serve as input variables for a model usually suffer from significant variability and so does exposure. Besides variations in global climate—even if neglecting extremes related to anthropogenic or natural climate change—the local climate is furthermore affected by topography, landscaping, infrastructure and buildings. In addition, variations in design and workmanship can have an effect on the finally resulting material climate inside a wooden component.

Thus, both the resistance *R* and the exposure (here, solicitation) *S* are varying. Therefore, a limit state function *Z(t)* can be written as follows according to Van de Kuilen (2007) (Fig. 8.18).

Following the laws of error propagation, the variation of service life to be expected is dramatically higher than those of resistance and exposure, and service lives are even more difficult to predict with sufficient reliability. Bongers *et al.* (2016) exemplarily showed the variety of parameters and instruments that can be used to display and illustrate the variation in resistance or durability respectively. Firstly, different measures can serve to quantify wood degradation or durability, respectively. Some are 'positive' such as 'service life'; some are 'negative' such as 'mass losses' or 'decay rate'. Secondly, different statistical parameters can be used to quantify the variation of the results—again depending on the measure chosen for quantifying decay itself. Mean, median, percentile and extreme values can be used, as well as confidence intervals. Furthermore, different graphical solutions are available to display the statistics such as correlation graphs, box-and-whisker-plots or simple tabular methods.

Finally, the different parameters and thus the quality of test data are strongly dependent on the exposure time. Larsson-Brelid *et al.* (2011) examined decay ratings from a total of more than 20,000 test stakes of different preservative-treated wood

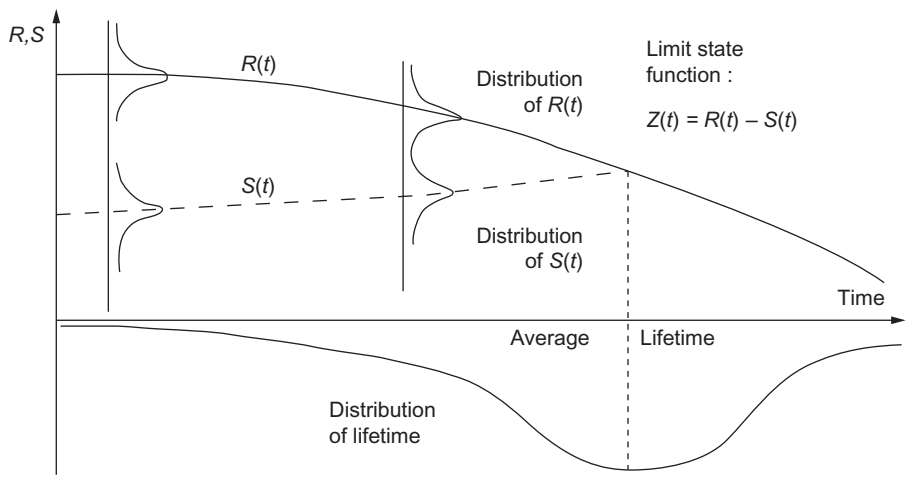


Fig. 8.18 Schematic representation of the distribution of lifetimes of structures (Van de Kuilen, 2007).

exposed in ground at different locations in Scandinavia with respect to the predictive potential of different statistical measures such as different percentiles of the specimens' lifetime. Results clearly showed that the early stages of decay are reflected in the long-time performance of the stakes. However, their overall conclusion was 'that the reliability of predicting the long-term performance of wood is lower the earlier in the test the information is extracted. Higher ratings and longer times in testing increase precision—or in other words: '*one has to pay time for safety"* (Larsson-Brelid *et al.*, 2011).

8.5.5 Concluding remarks

An ideal decay model should allow for predicting onset and progress of decay with high reliability using only input data that are available and easily accessible for an arbitrary location on the globe. Technically, a decay model should hence base on climate- and microclimate-affected parameters such as moisture content, temperature and the exposure time and indicators describing the resistance of the material or building component in question. Climate data are basically available for any location or can be interpolated with sufficiently high reliability. Moisture and temperature data from buildings and building components can be obtained using hygrothermal models and building physics simulation programs. Resistance data can be obtained from field or laboratory tests. They do exist for the majority of different types of bio-based building materials or can be easily generated if required. A decay model is the interface between an exposure model and a resistance model. Consequently, its predictive power depends on the reliability of the latter.

8.6 Mechanical performance modelling

J.W.G. van de Kuilen[*,†]*, W.F. Gard**
*TU Delft, Delft, The Netherlands
[†]TU München, München, Germany

8.6.1 Background

The service life of timber structures is of great importance for the management of the built environment. At the same time, the prediction of the service life is extremely complicated, as it depends on a great number of influencing factors, not the least economical ones. As it is a time-dependent issue, the estimation of the (remaining) service life is a challenging task, as it involves the assessment of the behaviour of wood under a mixture of loadings, which can be of mechanical, physical, biological and/or chemical in nature.

The service life of structures can be determined using several approaches that have been classified by the Joint Committee on Structural Safety (*JCSS*). The most complicated approaches comprise of so-called level III calculations, where for each variable of the structure (e.g. strength, stiffness, durability and loads), the actual or an estimated statistical distribution of the parameter is used. For wood, such distributions

are often unknown or have a high uncertainty level. The consequences of these uncertainties are that extremely high safety levels are aimed for, which often are not supported by practical evidence from existing buildings. According to the JCSS model code, three levels of calculations can be made with respect to the safety of a structure. Level I is fully deterministic, level III is fully probabilistic, whereas level II makes use of partial safety factors determined by level III calculations and that allows for some statistical variations to be included in the analysis.

Level III calculations often require extensive numerical calculations. Monte Carlo simulations, where properties of variables are randomly chosen from distribution functions, are examples of level III-type calculations. Level II calculations have some advantages over level III calculations since they give a better insight on the influence of the variables on the reliability of the structure. Often, level II calculations are performed to give a basis for design codes, which generally use level I calculations. Level I calculations have reached a stage where a separation is made between safety factors for loads and safety factors for strength values. This calculation method is often referred to as load and resistance factor design (*LRFD*). In this assay, emphasis will be given on the statistical distributions of material properties, γM factors and how durability aspects can be introduced into reliability-based design methods.

8.6.2 Reliability aspects

Independent of the calculation level, the reliability function can be written as shown in Eq. (8.45):

$$Z = R - S \tag{8.45}$$

where

R = resistance in this equation (strength/stiffness)
S = solicitation (load)

Whilst $Z > 0$, the structure is safe; when $Z = 0$, the structure is in the limit state of failure; and when $Z < 0$, the structure is unsafe.

Both the resistance (f_R) and the strength (f_S) can be written in the form of probability functions $f_R(r)$ and $f_S(s)$.

The probability function (P_f) of a system based on R and S is shown in Eq. (8.46):

$$P_f = f_R(r) \cdot f_S(s) \tag{8.46}$$

and the probability of failure is determined as shown in Eq. (8.47):

$$P_f = P(R - S \le 0) = \iint_{Z<0} f_R(r) \cdot f_S(s)\, dr ds \tag{8.47}$$

The development of this equation and calculations of the probability of failure are shown in different publications (Vrouwenvelder and Vrijling, 1987; Vrouwenvelder and Schießl, 1999; Sarja, 2002).

Basically, strength and loads have to be far enough away from each other in order to avoid structural failures. If the strength and loads are modelled as standard normal distributions, then Fig. 8.19 gives insight in the probability of failure. The greater the overlap between the two curves, the higher the probability of failure.

The strength R can be dependent on

- the materials used (e.g. solid wood and laminated veneer lumber),
- the climate (e.g. equilibrium wood moisture content and temperature),
- the execution of the building,
- the workmanship,
- the time.

An important feature is that timber has a time-dependent strength that is influenced by the load level. Consequently, the probability functions for the resistance and the solicitation are no longer independent from each other. However, assuming independence allows for easier calculations and still provides sufficient insight in the matter.

The load S (solicitation) can be dependent on

- the dead weight of the structure,
- the dynamic load,
- the use of the building,
- the climate (temperature and moisture).

The most recent design codes use a system with partial factors for load and resistance (γ-factors). Generally, the following condition has to be fulfilled:

$$\gamma_s S_k \leq \frac{R_k}{\gamma_M} \tag{8.48}$$

where

$\gamma M\ B$ = partial factor for material properties
R_k = characteristic value of the resistance
S_k = characteristic values of the load

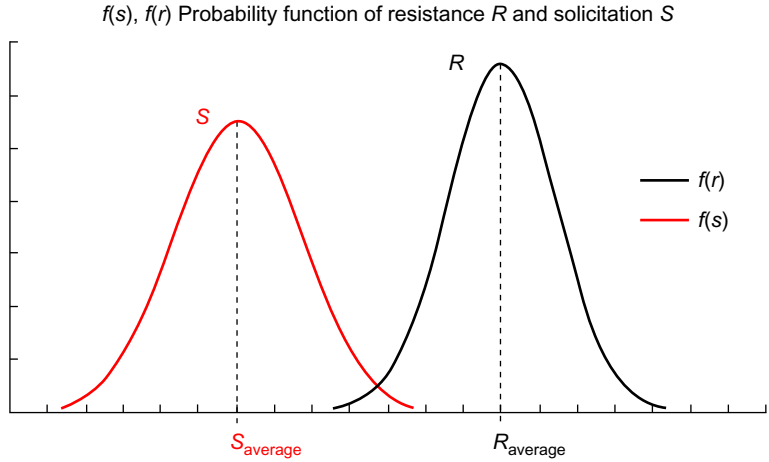


Fig. 8.19 Probability function of material resistance R and solicitation S.

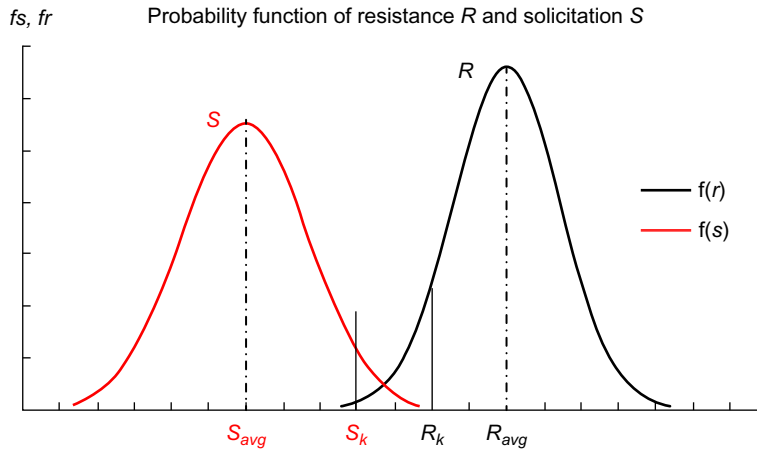


Fig. 8.20 Characteristic values of S_k and R_k (generally 95th/5th percentile values).

The characteristic values are generally defined as the 95th percentile value for the load and the 5th percentile value for the resistance. Depending on the type of structure, 95th percentile values of the load can be based on a return period of 15, 50 or 100 years. The characteristic values are shown in Fig. 8.20.

8.6.2.1 Time influence

So far, no influence of the time has been introduced in the current load and resistance factor design (LRFD) concept. It is, however, known that timber shows a duration of load effect. The material creeps and may fail after a certain period of time under load. This process can be described with damage accumulation models, which are in a way comparable with fatigue models for steel structures, although fatigue models count the number of loads and damage models for timber count the loading time. In reality, both the resistance and the load are varying over time, and the limit state function may consequently be written as shown in Eq. (8.49):

$$Z(t) = R(t) - S(t) \tag{8.49}$$

The structure is assumed not to have failed whilst $Z(t) > 0$. In Fig. 8.21, the lifetime distribution of structures is presented. Over time, the probability of failure increases.

The average value of the load S has been increased over time in Fig. 8.21. This may be caused by changes over time; for instance, when the wind or snow load increases because of climate changes, the water level may increase (sea level rise), or more common, the live load has changed due to conversion of the structure with consequent increase in load. Loads may eventually lead to failure of the timber or the joints.

In addition, timber shows a load, moisture and temperature-dependent resistance, so also the material properties vary over time. Consequently, Eq. (8.50) can be written as

$$Z(t) = R(s(\tau), t) - S(t) \tag{8.50}$$

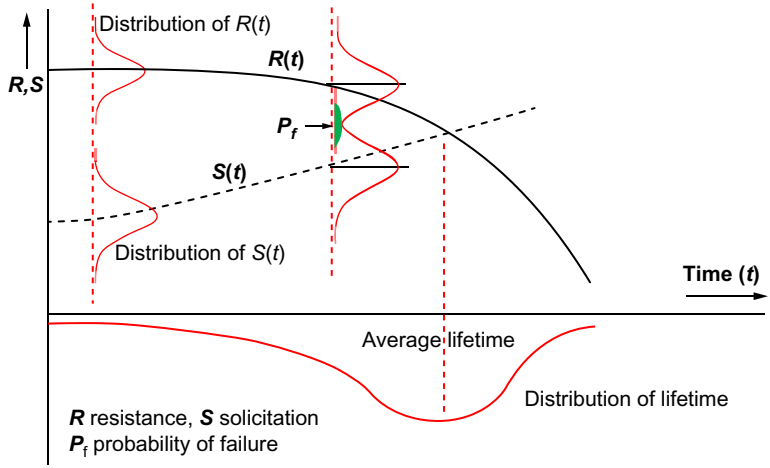


Fig. 8.21 Lifetime distribution of structures.

In order to assess the time-dependent safety, this equation has to be solved with respect to the material behaviour over time and the time-dependent loads.

8.6.3 Degradation phenomena

The loads on a structure have always to be smaller than the resistance of the timber (structural element) at each time during the complete service life of the structure. The material resistance to loads is the strength of the material, which in turn is a function of degradation processes over time. The degradation can be caused by various phenomena at the same time (Table 8.9). These phenomena occur at macro-, micro- and molecular level.

Mechanical overloading causes microdamages, which may grow to macrocracks and finally reducing the load-carrying capacity considerably. Different types of mechanical loads are classified in Eurocode EN 1991 (CEN, 1991) such as wind actions, snow and imposed loads. The load duration may have a considerable influence on the structure and may lead to a decrease in load-carrying capacity, apart from increased deformations of the structural element and joints (creep). Therefore, load durations have been classified in the Eurocode EN 1995 (CEN, 1995).

Physical loads are diverse. One main physical load is the fluctuation in wood moisture content whereby cracks on all material levels can occur. Most critical fluctuation of moisture content is between 8% and fibre saturation where the highest shrinkage and swelling takes place with the consequence of peak stress areas in the cell wall. In this context, Hearmon and Paton (1964) and Grossman (1976), among others, studied and reported on mechanosorptive effects in timber, a phenomenon that is still not fully understood.

Chemical loads such as fire-retardant treatments reduce the mechanical properties of timber (Kretschmann, 2010; Sweet and Winandy, 1999). In this connection, the cell-wall constituents are depolymerised so that the strength properties decrease.

Table 8.9 Loads on timber structures and its consequences

Loads	Consequences				Decrease of load carrying capacity
	Micro damages, for example, deformations	**Macro damages, for example, cracks**	**Strength variation without damage**	**Chemical degradation, for example, hemicellulose**	
Mechanical loads	X	X			
Physical loads					
• Moisture	X	X	X		
• Temperature	X	X	X	X	
• UV-radiation				X	
Chemical loads					
• Fire retardants				X	
• Wood preservatives				X	
• pH of the environment				X	
Biological loads					
• Fungi				X	
• Bacteria				X	
• Insects		X			
• Marine borers		X			

Degradation phenomena caused by microorganisms, insects and marine organisms are biological loads. Decay rates in timber depend on the type of biological attack. Decay rates are often expressed in term of loss of mass per time. However, loss of mass does not concern the engineer when assessing an existing structure. An engineer needs values for strength and stiffness of decayed timber, and he needs information about the distribution of decay in a cross section.

For softwoods, the bending strength can be predicted on the basis of known relationships between density and strength, but existing relationships cannot be used for decayed softwoods as the destruction on molecular level is responsible for rapid strength loss at small or moderate mass loss. For hardwoods, it is even more complex since the correlation between density and strength in hardwoods is weaker than for softwoods. Concerning decay, it would be an advantage if decay rates could be expressed as rate of penetration in millimetres per year (mm/year). Then, reduced cross sections and moments of resistance/inertia can be introduced.

8.6.3.1 Strength of decayed timber

Most types of biological attack cause a reduction in timber strength. Literature surveys about the relationship between type of decay and the strength are limited. In Fig. 8.22, results from an analysis of Liese and Stamer (1934) are shown for the influence of fungi on the compression strength of timber. The fungi shown are dry rot (*Merulius lacrymans)*, cellar rot (*Coniophora cerebella*) and pore fungi (*Poria vaporaria*). Kothe (1988) discussed the influence of the strength reduction as found by Liese and Stamer (1934) in structural elements.

Gard *et al.* (2014) found a relationship ($R^2 = 0.4$) between the compressive strength, the level of decay and the decayed area of mooring poles from the hardwood species azobe (*Lophira alata*) and basralocus (*Dicorynia* spp.). Wilcox (1978) gave an extensive literature review on the effects of early decay on the strength, making a distinction between brown rot and white rot, but did not specify the actual type of fungi. The amount of mass loss was related to several types of loading situations with bending, compression parallel to the grain and perpendicular to the grain being the most useful for the assessment of old structures.

8.6.4 Modelling approaches

Modelling attempts to determine strength losses of wood caused by various degradation phenomena have been done by Winandy and Lebow (2001). They believed that the earliest stages of strength loss in wood might be quantitatively modelled as a function of sequential degradation of hemicellulose side-chain sugars and thereafter the main-chain hemicellulose sugars. Advanced strength loss may happen when initial degradation of cellulose and lignin takes place. Their theoretical model could not fully describe the strength loss caused by the chemical depolymerisation, because of the complexity of the spatial arrangement of the polymers.

Nguyen *et al.* (2008) have done extensive investigations on service life modelling for timber structures in Australia. Three models have been developed: decay model for

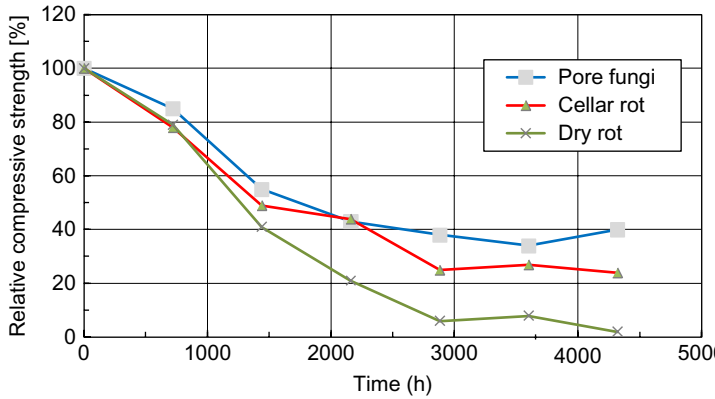


Fig. 8.22 Influence of decay on the compression strength of timber.

timber, atmospheric corrosion model for fasteners and embedded corrosion model for fasteners. Also the corrosion models for fasteners may be part of an entire service life estimation model for timber structures with multiple elements.

The failure criteria of their decay model are the depth of the degradation in the structural timber element. The time rate is a function of the wood species, the geometry of the element and the (micro) climate. The climate is defined as dose of wetness and temperature (see also Brischke and Rapp, 2010). A lag time before relevant decay starts has been introduced, which is related to the rate of decay (see also Fig. 8.23, where a lag time was identified for heartwood degradation in timber piles).

The necessary factors used in the model have been determined by measurements in experiments, field test and expert opinion.

For the resistance function $R(s(\tau),t)$, damage functions can be used. The applicability of these functions will be shown here, and in order to reduce complexity, the function chosen here is a simple exponential damage equation. In general, the damage function has a parameter α, which takes a value $0 \le \alpha \le 1$. For no damage, $\alpha = 0$, and failure occurs when $\alpha = 1$. This means that $1 - \alpha$ is a measure for the residual strength and the limit state. Backgrounds of damage models for timber can be found in Kuipers (1986), Gerhards and Link (1987), Foschi and Yao (1986), Caulfied (1985) and Van der Put (1986, 1989). Most models can be explained using the reaction kinetics approaches of Caulfied (1985) and Van der Put (1986, 1989), the latter being more complex.

The exponential damage function is defined as shown in Eq. (8.51):

$$\frac{d\alpha}{dt} = \exp\left(-a + b\frac{\sigma(t)}{\sigma_s}\right) \quad \text{and} \; \alpha(0) = 0 \tag{8.51}$$

Parameters a and b are to be determined from time to failure tests. Stress function $\sigma(t)$ represents the load history from the time of erection of the structure until the end of the time span under consideration. σ_s is equal to the short-term strength. Foschi and Yao (1986) developed a more complex damage function that may also be used. The difference between the Foschi and Yao model (Eq. 8.52 compared with Eq. 8.51) is relatively small and especially relevant for the final failure stage of structures (Van de Kuilen, 1999).

The Foschi and Yao model reads as the following:

$$\frac{d\alpha}{dt} = A\left(\sigma - \sigma_0\sigma_u\right)^B + C\left(\sigma - \sigma_0\sigma_u\right)^n \alpha \quad \text{and} \; \alpha(0) = 0 \tag{8.52}$$

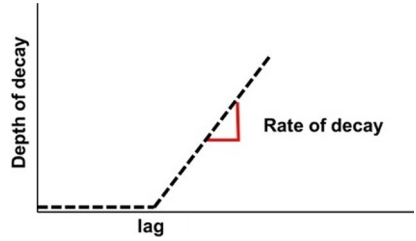


Fig. 8.23 Decay-time relationship (Nguyen *et al.*, 2008).

This model can be seen as a series development in α with σ_0 being a threshold level below which no damage is assumed to accumulate. This threshold level can be seen as a level similar to the level in fatigue models for structures. Below a certain stress, (or stress range) load cycles do not damage the structure nor contribute to crack growth.

The effect of crack formation in wood can be taken into account in a damage accumulation model by modifying the ratio between load and load-carrying capacity. These models assume that cross sections do not change over time, for instance, by assuming that the wood material properties are not influenced by decay and that the cross section is constant in its geometry. So, these models describe the duration of load problems for wood, without considering decay. A modification for changing material properties and cross sections can be found in Van de Kuilen (2000, 2007). A modified damage model is used considering degradation parameters that describe the time-dependent stress/strength ratio. This changes the standard exponential damage equation, as shown in Eq. (8.53):

$$\frac{d\alpha}{dt} = \exp\left(-a + b\frac{\sigma(t)}{f(t,T,\omega,\lambda,\mu.....)}\right) \tag{8.53}$$

The equation can be solved for different strength degradation developments by stepwise time integration. The wood strength in the denominator has now been made dependent on the time, moisture content, temperature and two degradation parameters λ and μ. Parameter λ describes the ratio of the cross section that is degraded as compared with the non-degraded section, whereas parameter μ describes the strength of degraded material, relative to non-degraded material. The parameters a and b (that are derived on the basis of time-to-failure tests) may also be affected, but as currently, no information is available whatsoever; these are kept constant based on sound wood investigations. Generally, one would expect a steeper time-to-failure line in the case of long-term testing of already degraded wood, similarly to the steeper time-to-failure lines for particle boards and several types of fibreboards. However, as the ratio $b/f(t,T,\omega\ldots)$ has now been made time-dependent and degraded material-dependent, this steeper ratio is considered to be included in the model.

8.6.5 Model applications

Modified damage accumulation models are suitable to estimate the service life of a structure, provided that besides mechanical loads, the physical and biological loads are considered.

8.6.5.1 Cracks in structures

Cracks are a typical degradation caused by physical processes. In old structures made of full-size wooden cross sections, drying is an important cause. More generally, the degradation can be caused by moisture variations (mostly drying), temperature

variations (also fire) and UV radiation. A typical example is the degradation of beams with large cross sections by drying cracks; see Fig. 8.24. Cracks may become more critical near the supports where shear stresses are higher.

More recent problems with cracks are found in glulam structures, especially in outdoor applications; see, for instance, Fig. 8.25, where a dark coloured glulam beam is exposed. The beam shows a number of cracks near the neutral axis and close to the support. From a mechanical viewpoint, this is the zone with the highest shear load with additional stresses due to normal forces and eccentricities in connections.

Fig. 8.24 Cracked beams in an existing structure and drying cracks near the neutral axis.

Fig. 8.25 Cracked glulam beam in outdoor climate. Cracks occur where the maximum shear stresses are expected.

A modified damage model is used by Van de Kuilen and Gard (2013) using degradation parameters that describe the time-dependent stress/strength ratio to estimate the ULS of the structure.

8.6.5.2 Pile foundations

Pile foundations (Fig. 8.26), where decay is present, do not necessarily lose their load-carrying capacity to such an extent that replacement becomes unavoidable. If the sapwood of timber piles is deteriorated, the remaining heartwood section might still have sufficient load-carrying capacity. Consequently, the ratio between decayed area and non-decayed area is an important parameter that can be used when the remaining lifetime of the structure has to be determined.

In Fig. 8.27, the results of parallel to the grain tests are shown, taken from small round specimen drilled from piles (Peek and Willeitner, 1981) to which test results from full-sized piles tested at Delft University have been added. Even though the data scatter, it is possible to conclude that the strength decreases with age. Both load and decay will cause a reduction in strength, and since the load level during the service life was not known, mechanical damage will have accumulated to a certain extent.

Calculations have been undertaken by Van de Kuilen (2000) to estimate the service life of the pile foundation. As an example, a ground-water table reduction after 50 years in service has been analysed for its consequences. The ground-water level has been lowered to such a level that the upper part of the pile became exposed to unsaturated soil conditions. Different decay patterns can be distinguished and have been taken into account in their service life and damage model, allowing prediction of the remaining service life.

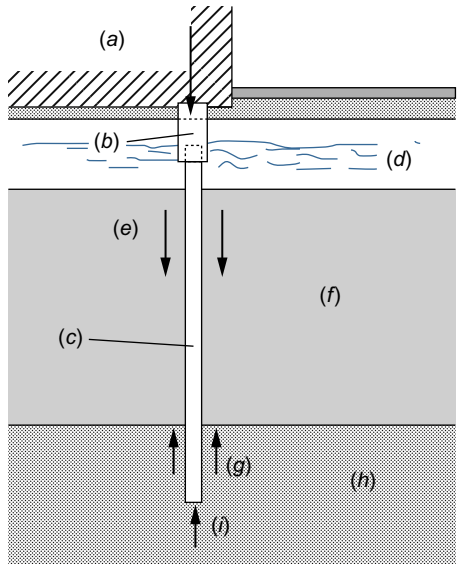


Fig. 8.26 (a) Structure, (b) concrete extension pile, (c) timber pile (tapered), (d) ground-water level, (e) negative skin friction, (f) weak clay, (g) positive skin friction, (h) load-bearing soil layer and (i) pile toe resistance.

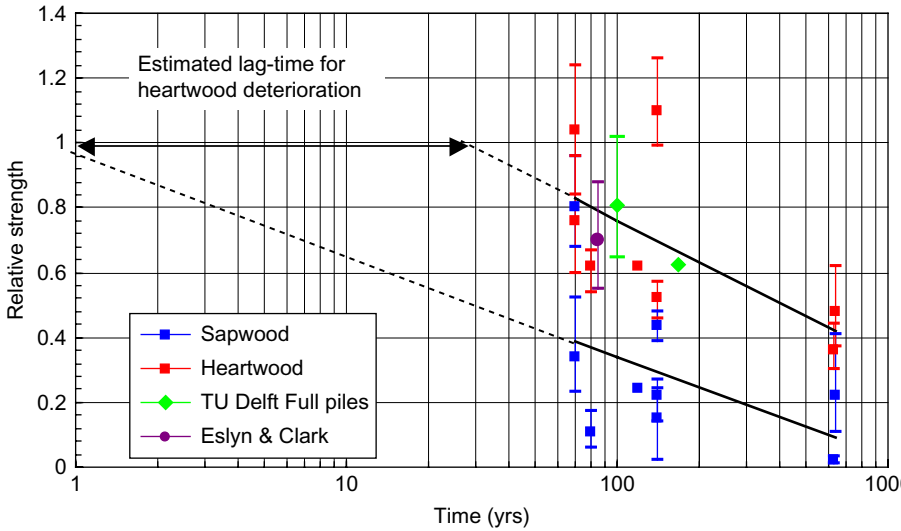


Fig. 8.27 Residual strength of degraded wood from foundations (Van de Kuilen, 2007).

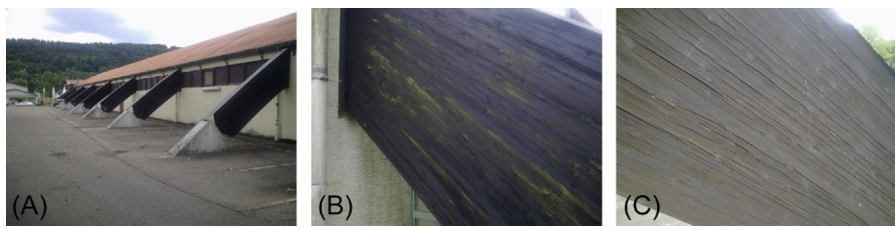


Fig. 8.28 (A) Glued-laminated timber beams as arches, (B) fungal decay on the rain exposed surface of the beam (green stain and black surface) and (C) delamination on the non-exposed side of the beam.

8.6.5.3 Glulam beam in outdoor climate

Beams that are exposed to different climates and produced under different circumstances can undergo inhibition or acceleration of physical degradation and possible crack formation. The timber structure in Fig. 8.28 is a glued-laminated structure where parts of the beam are exposed to the outdoor climate uncovered. On the surface of the beam exposed to the 'weather side' (wet), fungi decay and cracks can be observed. On the 'dry' site (Fig. 8.28C), delamination cracks are visible caused by shrinkage and swelling cycles.

In the model, applied mechanical, physical and biological loads are built in, which lead finally to failure of the structure.

Climate

It is assumed that the relative humidity and the temperature of the air vary over the year as follows in Eqs. (8.54) and (8.55), which is slightly more humid than the

uncontrolled indoor climate as measured in Van de Kuilen (1999) and is just above the boundary between service class 2 and 3 of Eurocode 5 (2005):

$$\mathrm{RH} = \mathrm{RH}_m + \mathrm{RH}_A \sin\left(\frac{2\pi t}{T} + \varphi_{rh}\right) = 75 + 20\sin\left(\frac{2\pi t}{T} + 91.25\right) \tag{8.54}$$

and

$$T_K = T_m + T_A \sin\left(\frac{2\pi t}{T} + \varphi_T\right) = +293 + 15\sin\left(\frac{2\pi t}{T}\right) \tag{8.55}$$

where

T_k = temperature,(K)
T_m = mean temperature of a year (°C)
T_A = amplitude of the temperature (°C)
T = time (a)
t = time (d)

The functions have been chosen such that the relative humidity has a phase shift of 91.25 days compared with the temperature. Consequently, a low temperature coincides with a high relative humidity and *vice versa* (see Fig. 8.29). In the case of the structure shown in Fig. 8.28, it is assumed that the mean annual moisture content is relatively high, and diffusion is hardly delayed in order to make the example not too complex. As the wood surfaces are directly exposed to the weather, diffusion is relatively fast. In addition, the end grain of the wood is directly accessible, allowing for fast moisture exchange. More elaborated models for moisture diffusion exist, but in the vicinity of the connections shown, these are not necessary.

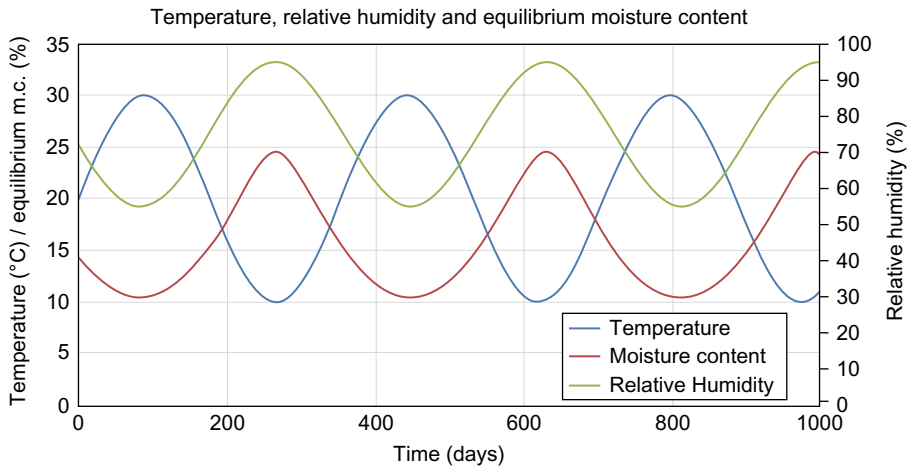


Fig. 8.29 Yearly variation in temperature, relative humidity and equilibrium moisture content.

On the basis of the temperature and relative humidity variations, the equivalent wood moisture content over the year is calculated using Bramhall's model (1979), without the time delay caused by diffusion (Eq. 8.56).

$$\omega_{emc} = \frac{\ln\left(\frac{\ln(\mathrm{RH}) + k_3}{k_2}\right)}{0.92 \ln k_1} \tag{8.56}$$

where

$k_1 = 1.0327 - 0.000674T$

$k_2 = 17.884 - 0.1432T + 0.0002363T^2$

$k_3 = -0.0251$

with T in Kelvin and RH the relative humidity in %.

The variation of the temperature, relative humidity and resulting equilibrium moisture content in the timber is shown in Fig. 8.29.

Structural assessment

The glued-laminated timber structure is analysed for the shear capacity at the support. The following assumptions are made:

Glulam	**strength class GL24h**
Width b_0 at $t=0$, Depth h_0 at $t=0$, Shear strength f_v at $\omega=12\%$, Moisture content dependency $\omega_{c,v}$, Load-carrying capacity in shear at $t=0$ and $\omega=12\,\%$,	$b_0=200$ mm $h_0=800$ mm $f_v=5$ N/mm^2 $\omega_{c,v}=1\,\%/\%$ $F_v=533$ kN

Load situation

Two load cases are analysed:

Load case 1—dead load of 100 kN and live load of 100 ± 10 kN (random component)

Load case 2—dead load of 100 kN and live load of 100 ± 10 kN (random component), annual snow of max. $100\,\mathrm{kN} \pm 50\,\mathrm{kN}$ for a maximum period of about 3 months per year.

Service life prediction without biological deterioration

In Figs. 8.30 and 8.31, the two load cases are presented for a period of 50 years, which is the most important reference period for structures. The relative load level is given, indication of the ratio between load and available strength. For the representation, no safety factors have been applied. The green line indicates that the load level varies over the year, not only because of the random load components but also because of the moisture dependency of the shear strength. The blue line indicates the damage development; the red line indicates the remaining load-carrying capacity, relative to the original one of 533 kN. Over the years, only a very small reduction in load-carrying capacity can be observed for 'load case 1'. The model used is a linear exponential damage accumulation.

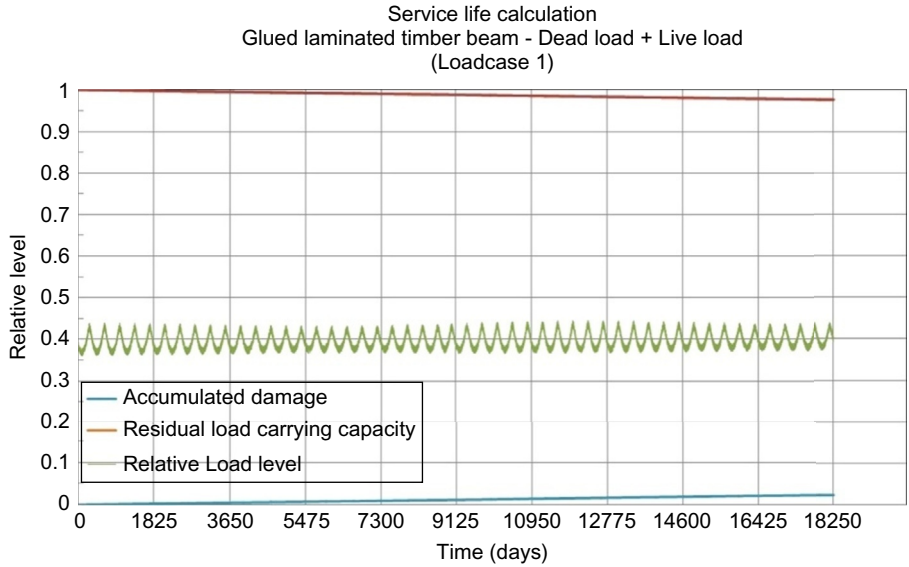


Fig. 8.30 Service life calculation for 50 years, load case 1 (dead load + live load).

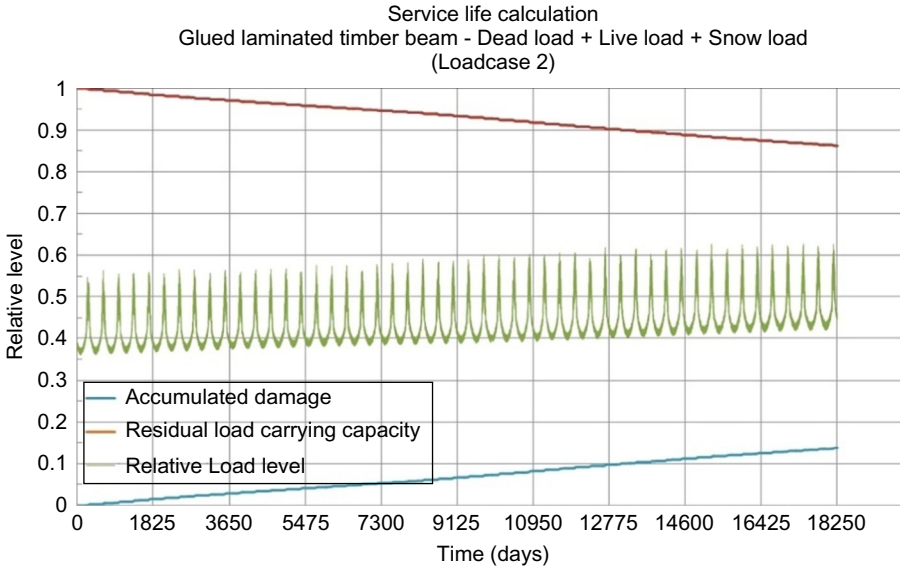


Fig. 8.31 Service life calculation for 50 years, load case 2 (dead load + live load + snow load).

For 'load case 2' (Fig. 8.31), it can be observed that the damage accumulated over the years is higher than for 'load case 1', roughly quadrupled. This indicates that the contribution of the snow load to the damage accumulation is not negligible, even though acting for not more than three months per year.

Service life prediction with biological deterioration

In the more complicated situation of an assessment of a structure as given in Fig. 8.28, the biological deterioration is now introduced in the damage equation. Apart from the dead, live and occasional snow load, the load-carrying capacity is decreasing over time because of the biological decay. As it takes time for biological decay to start, a delay time is incorporated. In contradiction to heartwood decay in timber piles that has a relatively long decay time because of the protection of the sapwood layer (Van de Kuilen, 2007), in this case, the delay time is relatively short and more comparable with the dose concept for above-ground decay (Brischke and Rapp, 2010). As can be seen from Fig. 8.28, the structure has been suffering from high humidity over longer times. Consequently, it can be assumed that the cross section suffers from biological degradation and thus reduced load-carrying capacity in those parts that are decayed. Not counting the decayed area as functional (able to carry load), the remaining healthy cross section is now exposed to higher stresses. This increased stress level leads to more mechanical damage at the micro scale, thus shortening the (remaining) service life of the structure. For the example calculation of the service life, the following data are used for biological deterioration. The decay is assumed to be present on all four sides of the cross section:

Delay time t' for biological decay	$t' = 5$ years
Biological decay rate r_{bd}	0.5 mm/year when $\omega \geq 21\,\%$

In Fig. 8.32, the green line, indicating the relative load level, slowly starts to increase after the delay time of 5 years. Consequently, the damage per time step increases more than in Fig. 8.31, and the residual load-carrying capacity after 50 years is still more than sufficient, as not more than 5% of strength reduction is present at time $t = 18250$ days.

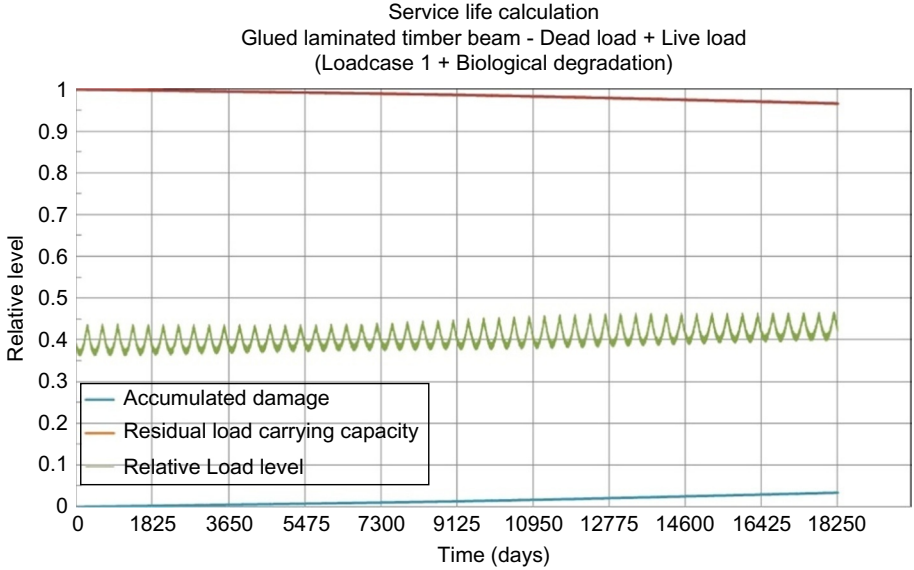


Fig. 8.32 Service life calculation for 50 years, load case 1 (dead load + live load) and biological deterioration 0.5 mm/ year with a delay time of 5 years.

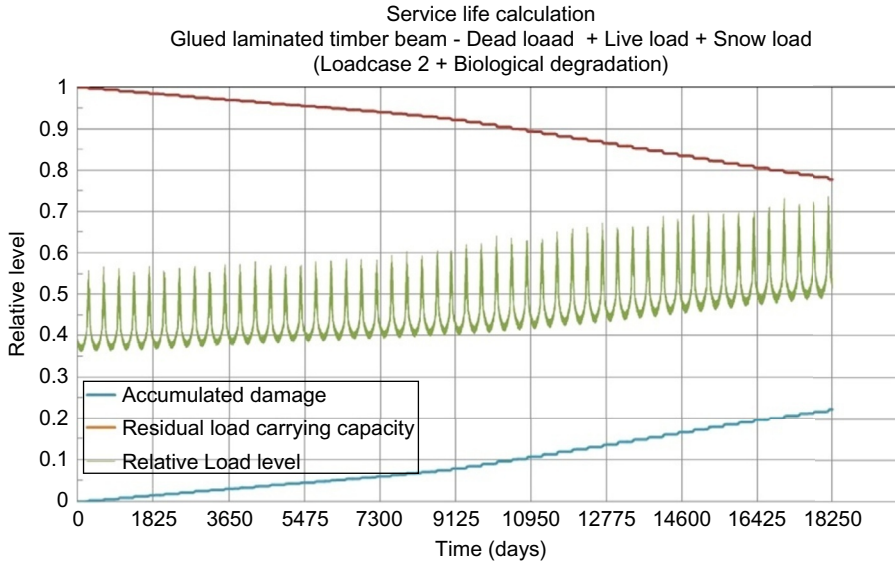


Fig. 8.33 Service life calculation for 50 years, load case 2 (dead load + live load + snow load) and biological deterioration 0.5 mm/ year with a delay time of 5 years.

In Fig. 8.33, the same structure is analysed for load case 2, that is, snow load included, and it becomes clear that in this case, the accumulated damage over time becomes much more critical. After 50 years, the residual load-carrying capacity is close to the actual load. When no measures are taken, the structure will inevitably collapse.

8.6.6 Conclusions

It is shown that with a modified damage model, the service life of structures can be analysed. A combination of mechanical loads and biological or physical deterioration of the wooden elements can be simulated, and possible consequences can be analysed. From the presented case study, it becomes clear that when structures are not seriously suffering from decay, the probability of structural collapse remains small. On the contrary, if decay is progressing more rapidly than 0.5 mm/year at moisture contents above the critical level of 21% as assumed in the example study, the load-carrying capacity decreases very rapidly and structural failure is imminent.

References

Abu-Tair, A.I., McParland, C., Lyness, J.F., Nadjai, A., 2002. Predictive models of deterioration rates of concrete bridges using the factor method based on historic inspection data. In: Proceedings of the 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia, 2002. Paper 262.

Angst, V., 2012. Moisture-Induced Stresses in Glulam (Doctoral Thesis). Norwegian University of Science and Technology, Trondheim, Norway.

Ayerst, J., 1969. The effect of moisture and temperature on growth and spore germination in some fungi. J. Stored Prod. Res. 5, 127–141.

Beesley, J., Crefffield, J.W., Saunders, I.W., 1983. An Australian test for decay in painted timbers exposed to the weather. For. Prod. J. 33, 57–63.

Bok, G., Johansson, P., Jermer, J., 2012. Mould growth on wood-based materials – a simulated in-service study. Proceedings IRG Annual Meeting, Kuala Lumpur, Malaysia, IRG/WP 12-20503.

Bok, G., Johansson, P., Ekstrand-Tobin A, Bardage, S., 2013. Critical moisture levels and mould resistance of five different wood treatments. Proceedings IRG Annual Meeting (ISSN 2000-8953) Stockholm, Sweden 16–20 June, IRG/WP 13-30632.

Bongers, F., Brischke, C., Van den Bulcke, J., De Windt, I., Militz, H., Van Acker, J., 2016. How to Express Variability in Field Testing. The International Research Group on Wood Protection, IRG/WP/16-20594.

Bramhall, G., 1979. Mathematical model for lumber drying, Part 1, Principles involved. Wood Sci. 12 (1), 15–21.

Brischke, C., Meyer-Veltrup, L., 2015. Modelling wood decay caused by brown rot fungi. Mater. Struct. http://dx.doi.org/10.1617/s11527-015-0719-y.

Brischke, C., Rapp, A.O., 2010. Service life prediction of wooden components—part 1: determination of dose response functions for above ground decay. The International Research Group on Wood Protection, Stockholm. IRG/WP/10-20439.

Brischke, C., Rapp, A.O., 2011. Potential impacts of climate change on wood deterioration. Int. Wood Prod. J. 1, 85–92.

Brischke, C., Thelandersson, S., 2014. Modelling the outdoor performance of wood products—a review on existing approaches. Constr. Build. Mater. 66, 384–397.

Brischke, C., Rapp, A.O., Bayerbach, R., 2006. Decay influencing factors: a basis for service life prediction of wood and wood-based products. Wood Mater. Sci. Eng. 1, 91–107.

Brischke, C., Welzbacher, C.R., Rapp, A.O., Augusta, U., Brandt, K., 2009. Comparative studies on the in-ground and above-ground durability of European oak heartwood (*Quercus petraea* Liebl. and *Quercus robur* L.). Eur. J. Wood Wood Prod. 67, 329–338.

Brischke, C., Lauenstein, B., Bilstein, M., Bornemann, T., Rapp, A.O., 2010. Service life prediction of wooden components—Part 2: impact of material, exposure and design details. The International Research Group on Wood Protection, Stockholm. IRG/WP/10-20440.

Brischke, C., Frühwald Hansson, E., Kavurmaci, D., Thelandersson, S., 2011. Decay hazard mapping for Europe. The International Research Group on Wood Protection, Stockholm. IRG/WP/11-20463.

Brischke, C., Meyer, L., Alfredsen, G., Humar, M., Francis, L., 2012. Durability of timber products—part 2: Proposal for an IRGWP—durability data base. The International Research Group on Wood Protection, Stockholm IRG/WP/12-20497.

Brischke, C., Meyer, L., Bornemann, T., 2013a. The potential of moisture content measurements for testing the durability of timber products. Wood Sci. Technol. 47, 869–886.

Brischke, C., Meyer, L., Bornemann, T., Bilstein, M., Lauenstein, B., Lück, J.M., et al., 2013b. Service life of timber components: prognosis based on 3 years high-frequency monitoring. Eur. J. Wood Wood Prod. 71, 79–90.

Brischke, C., Alfredsen, G., Flæte, P.-O., Humar, M., Isaksson, T., Meyer, L., 2015. The combined effect of wetting ability and durability on field performance—verification of a new prediction approach. The International Research Group on Wood Protection, Stockholm. IRG/WP/15-20565.

Carll, C.G., 2009. Decay hazard (Scheffer) Index values calculated from 1971-2000 climate normal data. General Technical report FPL-GTR-179, United States Department of Agriculture, Forest Service, Forest Products Laboratory.

Caulfied, D.F., 1985. A chemical kinetics approach to the duration-of-load problem in wood. Wood Fiber Sci. 17 (4), 504–521.

CEN, 1991. EN:1991. Eurocode 1 (2002) Actions on Structures Part 1–7. European Committee for Standardization, Brussels, Belgium.

CEN, 1995. EN:1995. Eurocode 5 (2005) Design of Timber Structures—Part 1-1: General—Common Rules and Rules for Buildings. European Committee for Standardization, Brussels, Belgium.

CEN, 2015. EN 252:2015. Field Test Method for Determining the Relative Protective Effectiveness of a Wood Preservative in Ground Contact. European Committee for Standardization, Brussels, Belgium.

CEN, 2016. EN 350:2016. Durability of Wood and wood-based products—Testing and classification of the durability to biological agents of wood and wood-based materials. European Committee for Standardization, Brussels, Belgium.

Cornick, S., Djebbar, R., Dalgliesh, W., 2003. Selecting moisture reference years using a moisture index approach. Build. Environ. 38, 1367–1379.

Creemers, J., de Meijer, M., Zimmermann, T., Sell, J., 2002. Influence of climatic factors on the weathering of coated wood. Holz Roh Werkst. 60, 411–420.

Daniotti, B., Spagnolo, S.L., Chevalier, J.L., Hans, J., Chorier, J., 2010. An international service life database: the grid definition for an actual implementation of factor methods and service life prediction. In: CIB 2010 World Congress. CIB, Rotterdam, pp. 228–238.

Dawson, B.S.W., Göttgens, A., Hora, G., 2005. Natural weathering performance of exterior wood coatings on *Pinus sylvestris* and *Pinus radiata* in Germany and New Zealand. J. Coat. Technol. Res. 2 (7), 539–546.

De Groot, R.C., 1982. An assessment climate index in predicting wood decay in houses. Durab. Build. Mater. 1, 169–174.

Dickinson, D., 2005. The factor method in wood preservation—a proposal for future progress from the COST E37 Task Force. In: COST E37 5th Meeting of Task force "Performance Classification," Oslo, Norway.

Fortino, S., Mirianon, F., Toratti, T., 2009. A 3D moisture-stress FEM analysis for time dependent problems in timber structures. Mech. Time-Depend. Mater. 13, 333–356.

Fortino, S., Genoese, A., Genoese, A., Nunes, L., Palma, P., 2013a. Numerical modelling of the hygro-thermal response of timber bridges during their service life: a monitoring case-study. Constr. Build. Mater. 47, 1225–1234.

Fortino, S., Hradil, P., Genoese, A., Genoese, A., Pousette, A., Fjellström, P.A., 2016. A multi-Fickian hygro-thermal model for timber bridge elements under Northern Europe climates. In: Proceedings of World Conference on Timber Engineering (WCTE 2016), Vienna, Austria.

Foschi, R.O., Yao, R.C., 1986. Another look at three duration of load models. In: CIB/W18 Timber Structures, Paper 19-9-1, Meeting 19, September 1986, Florence, Italy.

Fragiacomo, M., Fortino, S., Tononi, D., Usardi, I., Toratti, T., 2011. Moisture-induced stresses perpendicular to grain in timber sections exposed to European climates. Eng. Struct. 33, 3071–3078.

Francis, L.P., Norton, J., 2006. Predicting the decay resistance of timber above-ground. 1. Climate effects. The International Research Group on Wood Protection, Stockholm IRG/WP/06-20330.

Frandsen, H.L., 2007. Selected Constitutive Models for Simulating the Hygromechanical Response of Wood (Dissertation no. 10). Department of Civil Engineering, Aalborg University, Denmark.

Fredriksson, M., Wadsö, L., Johansson, P., 2013. Methods for determination of duration of surface moisture and presence of water in gaps in wood joints. Wood Sci. Technol. 47, 913–924.

Fredriksson, M., Wadsö, L., Johansson, P., Ulvcrona, T., 2014. Microclimate and moisture content profile measurements in rain exposed Norway spruce (*Picea abies* (L.) Karst.) joints. Wood Mater. Sci. Eng. http://dx.doi.org/10.1080/17480272.2014.965742.

Frühwald, E., Serrano, E., Toratti, T., Emilsson, A., Thelandersson, S., 2007. Design of safe timber structures—how can we learn from failures in concrete, steel and timber? Report TVBK-3053, Lund University, Sweden.

Frühwald Hansson, E., Brischke, C., Meyer, L., Isaksson, T., Thelandersson, S., Kavurmaci, D., 2012. Durability of timber outdoor structures—modelling performance and climate impacts. In: World Conference on Timber Engineering, Auckland, New Zealand, 16–19 July 2012.

Gard, W.F., Cabrera de Diego, M., de Kuilen JWG, Van, 2014. Influence of material deterioration on strength properties of hydraulic timber structures. In: WCTE 2014, Quebec, Canada, Paper 657.

Genoese, A., Genoese, A., Fortino, S., Hradil, P., 2013. A numerical approach for the hygrothermal monitoring of timber structures under environmental conditions. Structural Health Assessment of Timber Structures. Advanced Materials Research, vol. 778. Trans Tech Publications, Switzerland.

Gereke, T., Niemz, P., 2010. Moisture-induced stresses in spruce cross-laminates. Eng. Struct. 32, 600–606.

Gerhards, C.C., Link, C.L., 1987. A cumulative damage model to predict load duration characteristics of lumber. Wood Fiber Sci. 19 (2), 147–164.

Ghosh, S.C., Militz, H., Mai, C., 2009. Natural weathering of Scots pine (*Pinus silvestris* L.) boards modified with functionalized commercial silicone emulsions. BioResources 4 (2), 659–673.

Grinda, M., Carey, J., 2004. The Cost Euro Index for fungal decay—five years results. In: COST E22, Estoril, Portugal, 22–23 March 2004.

Grossman, P.U.A., 1976. Requirements for a model that exhibits mechano-sorptive behavior. Wood Sci. Technol. 10, 163–168.

Grossman, D.M., 1994. Errors Caused by Using Joules to Time Laboratory and Outdoor Exposure Tests. ASTM STP 1202, Philadelphia, PA.

Häglund, M., 2007. Moisture content penetration in wood elements under varying boundary conditions. Wood Sci. Technol. 41, 477–490.

Hasegawa, M., 1996. Relationships between wood protection and climate indexes. Mokuzai Hozon. 22, 2–9.

Hearmon, R.F.S., Paton, J.M., 1964. Moisture content changes and creep of wood. For. Prod. J. 14 (8), 357–359.

Hukka, A., Viitanen, H., 1999. A mathematical model of mould growth on wooden material. Wood Sci. Technol. 33, 475–485.

Isaksson, T., Thelandersson, S., 2013. Experimental investigation on the effect of detail design on wood moisture content in outdoor above ground applications. Build. Environ. 59, 239–249.

Isaksson, T., Thelandersson, T., Ekstrand-Tobin, A., Johansson, P., 2010. Critical conditions for onset of mould growth under varying climate conditions. Build. Environ. 45, 1712–1721.

Isaksson, T., Brischke, C., Thelandersson, S., 2013. Development of decay performance models for outdoor timber structures. Mater. Struct. 46, 1209–1225.

Isaksson, T., Thelandersson, S., Jermer, J., Brischke, C., 2014. Beständighet för utomhusträ ovan mark. Guide för utformning och materialval. Rapport TVBK-3066, Lund University, Division of Structural Engineering, Lund, Sweden.

ISO, 2008. ISO 13823:2008. General Principles on the Design of Structures for Durability. International Organization for Standardization. International Organization for Standardization, Geneva, Switzerland.

ISO, 2011. ISO 15686-1:2011. Buildings and Constructed Assets—Service Life Planning—Part 1: General Principles and Framework. International Organization for Standardization, Geneva, Switzerland.

Johansson, P., 2012. Critical Moisture Conditions for Mould Growth on Building Materials (Licentiate Thesis). Report TVBH-3051. Division of Building Physics, Lund University, Lund, Sweden.

Johansson, P., Jermer, J., 2010. Mould growth on wood-based materials – a comparative study. Proceedings IRG Annual Meeting, Biarritz, France, IRG/WP 10-20455.

Johansson, P., Bok, G., Ekstrand-Tobin, A., 2013. The effect of cyclic moisture and temperature on mould growth on wood compared to steady-state conditions. Build. Environ. 65, 178–184.

Jönsson, J., 2005. Moisture Induced Stresses in Timber Structures (Dissertation). Technical report TVBK-1031. Division of Structural Engineering, Lund University, Sweden.

Köse, G., Temiz, A., Akbaş, S., Özkan, O.E., 2013. Effect of climate factors on wood veneers exposed to outdoor conditions in Black Sea region. In: International Caucasia Forestry Symposium, Bartin, Turkey, 24–26 October 2013. pp. 870–877.

Kothe, E., 1988. Auswirking van Holzscha¨den durch Pilze und Insekten auf die Standsicherheit van Holzbauwerken—eine Bestandsaufnahme. Bautechniek 75, 552–558. Heft 8.

Kretschmann, D.E., 2010. Mechanical properties of wood. In: Wood Handbook—Wood as an Engineering Material. General technical report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 508 p.

Krus, M., Sedlbauer, K., Zillig, W., Künzel, H.M., 2001. A new model for mould prediction and its application on a test roof. In: Proceedings of the 2nd International Conference on "The Current Problems of Building Physics in the Rural Building," Cracow, Poland.

Kuipers, J., 1986. Effect of age and/or load on timber strength—CIB-W18 paper 19-6-1. In: CIB/IUFRO Meeting, Florence, Italy.

Larkin, G.M., Laks, P.E., 2008. To decay or not to decay: an accelerated field test of the validity of the Scheffer Index. The International Research Group on Wood Protection, Stockholm. IRG/WP/08-20392.

Larsson-Brelid, P., Brischke, C., Pilgård, A., Hansson, M., Westin, M., Rapp, A.O., Jermer, J., 2011. Methods of field data evaluation—time versus reliability. The International Research Group on Wood Protection, Stockholm. IRG/WP/11-20466.

Lebow, S.T., Highley, T., 2008. Regional biodeterioration hazards in the United States. In: Schultz, T.P., Militz, H., Freeman, M.H., Goodell, B., Nicholas, D.D. (Eds.), Development of Commercial Wood Preservatives: Efficacy, Environmental, and Health Issues. ACS Symposium Series, vol. 982. American Chemical Society, Washington, DC, pp. 120–141.

Liese, J., Stamer, J., 1934. Angewandte Botanik Bd 16, 363.

Lisø, K.R., Hygen, H.O., Kvande, T., Thue, J.V., 2006. Decay potential in wood structures using climate data. Build. Res. Inf. 34, 546–551.

MacKenzie, C.E., Wang, C.-H., Leicester, R.H., Foliente, G.C., Nguyen, M.N., 2007. Timber Service Life Guide. Forest and Wood Products Limited, Victoria.

Meyer, L., Brischke, C., 2015. Fungal decay at different moisture levels of selected European-grown wood species. Int. Biodeterior. Biodegrad. 103, 23–29.

Meyer-Veltrup, L., Brischke, C., Alfredsen, G., Humar, M., Flæte, P.-O., Isaksson, T., Larsson Brelid, P., Westin, M., Jermer, J., 2017. The combined effect of wetting ability and

durability on outdoor performance of wood – development and verification of a new prediction approach. Wood Sci. Technol. http://dx.doi.org/10.1007/s00226-017-0893-x.
Moon, H.J., 2005. Assessing Mold Risks in Buildings Under Uncertainty (PhD Thesis). Georgia Institute of Technology.
Morris, P.I., Wang, J., 2008. A New Decay Hazard Map for North America Using the Scheffer Index. The International Research Group on Wood Protection, Stockholm. IRG/WP/08-10672.
Morris, P.I., Wang, J., 2011. Scheffer index as preferred method to define decay risk zones for above ground wood in building codes. Int. Wood Prod. J. 2, 67–70.
Musci, A., 2016. Effects of moisture content on timber structural elements. Case-study: Vihantasalmi bridge (MSc Thesis). University of Brescia, Italy.
Nambu, Y., Ikaga, T., 2011. Developing a Life Cycle Assessment (LCA) database of wood materials based on international field survey. In: SB11 Helsinki World Sustainable Building Conference, 18–21 October 2011.
Nguyen, M.N., Leicester, R.H., Wang, C.H., 2008. Service Life Models for Timber Structures Protected in Building Envelope. Manual No. 9, CSIRO Sustainable Ecosystems, Highett, Australia, 57p.
Niklewski, J., Fredriksson, M., Isaksson, T., 2016a. Moisture content prediction of rain-exposed wood: test and evaluation of a simple numerical model for durability applications. Build. Environ. 97, 126–136.
Niklewski, J., Frühwald Hansson, E., Brischke, C., Kavurmaci, D., 2016b. Development of Decay Hazard Maps Based on Decay Prediction Models. The International Research Group on Wood Protection, Stockholm. IRG/WP/16-20588.
Norén, J., 2001. Assessment and Mapping of Environmental Degradation Factors in Outdoor Applications (Dissertation). KTH Royal Institute of Technology, Stockholm, Sweden.
Ormarsson, S., Gíslason, O.V., 2016. Moisture induced stresses in glulam frames. Eur. J. Wood Wood Prod. 74, 307–318.
Pandley, K.K., 2005. A note on the influence of extractives on the photo-discoloration and photo-degradation of wood. Polym. Degrad. Stab. 87 (2), 375–379.
Peek, R.D., Willeitner, H., 1981. Behaviour of wooden pilings in long time service. In: Proceedings of Tenth Conference International Society of Soil Mechanics and Foundations, Vol. III, 9/23, Stockholm, Sweden, pp. 147–152.
Pfeffer, A., Mai, C., Militz, H., 2012. Weathering characteristics of wood treated with water glass, siloxane or DMDHEU. Eur. J. Wood Wood Prod. 70 (1–3), 165–176.
Pietrzyk, K., 2015. A systemic approach to moisture problems in buildings for mould safety modelling. Build. Environ. 86, 50–60.
Rubel, G.O., 1997. A non-intrusive method for the measurement of water vapour sorption by bacterial spores. J. Appl. Microbiol. 83, 243–247.
Rüther, P., Time, B., 2016. External wood claddings—performance criteria, driving rain and large-scale water penetration methods. Wood Mater. Sci. Eng. 10 (3), 287–299.
Sadovský, Z., Koronthályová, O., Matiasovský, P., Mikulová, K., 2014. Probabilistic modelling of mould growth in buildings. J. Build. Phys. 37, 348–366.
Salminen, K., Viitanen, H., Paajanen, L., Lähdesmäki, K., Strander, T., Vinha, J., et al., 2009. Mould growth on building materials in laboratory and field experiments (in Finnish). In: Rakennusfysiikka 2009. Symposium Proceedings, Tampere. pp. 219–229.
Sandak, J., Sandak, A., Riggio, M., 2015a. Multivariate analysis of multi-sensor data for assessment of timber structures: principles and applications. Constr. Build. Mater. 101 (2), 1172–1180.
Sandak, J., Sandak, A., Riggio, M., 2015b. Characterization and monitoring of surface weathering on exposed timber structures with multi-sensor approach. Int. J. Archit. Herit. 9, 674–688.

Sandak, A., Sandak, J., Burud, I., Gobakken, L.R., 2016a. Weathering kinetics of thin wood veneers assessed with NIR. J. Near Infrared Spectrosc. 24, 549–553.

Sandak, A., Sandak, J., Burud, I., Gobakken, L.R., Noël, M., 2016b. Expert Versus Multi-Sensor Evaluation of Wood Samples After Short Term Weathering. In: The International Research Group on Wood Protection, IRG/WP 16-20587.

Sandberg, D., 1999. Weathering of radial and tangential wood surfaces of pine and spruce. Holzforschung 53 (4), 355–364.

Sarja, A., 2002. Reliability based life cycle design and maintenance planning. In: JCSS Workshop on Reliability Based Code Calibration, ETH Zurich, Switzerland, 21–22 March 2002. http://www.jcss.byg.dtu.dk (Sep. 2016).

Scheffer, T.C., 1971. A climate index for estimating potential for decay in wood structures above ground. For. Prod. J. 21, 25–31.

Schmidt, O., 2006. Wood and Tree Fungi—Biology, Damage, Protection, and Use. Springer, Berlin.

Sedlbauer, K., 2001. Vorhersage von Schimmelpilzbildung auf und in Bauteilen (PhD Thesis). University of Stuttgart, Germany.

Setliff, E.C., 1986. Wood decay hazard in Canada based on Scheffer's climate index formula. For. Chron. (October), 456–459.

Smeland, K.A., Liland, K.H., Sandak, J., Sandak, A., Gobakken, L.R., Thiis, T.K., et al., 2016. Weather degradation of thin wood samples assessed with NIR hyperspectral imaging in transmission mode. J. Near Infrared Spectrosc. 24, 595–604.

Smith, S.L., Hill, S.T., 1982. Influence of temperature and water activity on germination and growth of *Aspergillus restrictus* and *Aspergillus versicolor*. Trans. Br. Mycol. Soc. 79, 558–560.

Stirling, R., Alfredsen, G., Brischke, C., De Windt, I., Francis, L.P., Frühwald Hansson, E., et al., 2016. Global Survey on Durability Variation—On the Effect of the Reference Species. In: The International Research Group on Wood Protection, Stockholm. IRG/WP/16-20573.

Svensson, S., Turk, G., Hozjan, T., 2011. Predicting moisture state of timber members in a continuously varying climate. Eng. Struct. 33, 3064–3070.

Sweet, M.S., Winandy, J.E., 1999. Influence of DP of cellulose and hemicellulose on strength loss in fire-retardant-treated Southern Pine. Holzforschung 53, 311–317.

Thelandersson, S., Isaksson, T., 2013. Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions. Build. Environ. 65, 18–25.

Thelandersson, S., Isaksson, T., Niklewski, J., 2014. Fuktsäker utformning av klimatskiljande byggnadsdelar med fuktkänsliga material - Vägledning för projektering och riskvärdering. Rapport TVBK-3065, ISSN-0349-4969, ISBN 978-91-979543-6-5, Lunds Tekniska Högskola, Inst. för Bygg- och Miljöteknologi.

Thelandersson, S., Isaksson, T., Suttie, E., Frühwald, H.E., Toratti, T., Grüll, G., et al., 2011. Quantitative Design Guideline for Wood in Outdoor Above Ground Applications. The International Research Group on Wood Protection, Stockholm. IRG/WP/11-20465.

Thiis, T.K., Burud, I., Kranitis, D., Gobakken, L.R., 2016. Simulation of Surface Climate and Mould Growth on Wooden Facades. The International Research Group on Wood Protection, Stockholm. IRG/WP 16–20585.

Tsuchikawa, S., Inoue, K., Mitsui, K., 2004. Spectroscopic monitoring of wood characteristics variation by light-irradiation. For. Prod. J. 54 (11), 71–76.

Van de Kuilen, J.W.G., 1999. Duration of Load Effects in Timber Joints (Ph.D. Thesis). Delft University of Technology, The Netherlands.

Van de Kuilen, J.W.G., 2000. Reliability assessment of timber structures. In: Wittmann, F.H., Verhoef, L.G.W. (Eds.), Maintenance and Restrengthening of Materials and

Structures—Wooden Structures. Aedificatio Publishers, Freiburg, Germany. ISBN: 3-931681-47-5.
Van de Kuilen, J.W.G., 2007. Service life modeling of timber structures, RILEM. Mater. Struct. 40, 151–161. http://dx.doi.org/10.1617/s11527-006-9158-0.
Van de Kuilen, J.W.G., Gard, W.F., 2013. Damage assessment and residual service life estimation of cracked timber beams. In: Piazza, M., Riggio, M. (Eds.), Advanced Materials Research. Structural Health Assessment of Timber Structures. Proceeding of the 2nd International Conference on Structural Health Assessment of Timber Structures (SHATIS'13), vol. 778. Trans Tech Publications, Durnten-Zurich, pp. 402–409.
van der Put, T.A.C.M., 1986. A model of deformation and damage processes based on the reaction kinetics of bond exchange. In: CIB/IUFRO Meeting 1986, Florence, Italy. Paper 19-9-3.
van der Put, T.A.C.M., 1989. Deformation and Damage in Processes in Wood (Doctoral Thesis). Delft University of Technology, Delft, The Netherlands.
Vereecken, E., Roels, S., 2012. Review of mould prediction models and their influence on mould risk evaluation. Build. Environ. 51, 296–310.
Viitanen, H., 1994. Factors affecting the development of biodeterioration in wooden constructions. Mater. Struct. 27 (172), 483–493.
Viitanen, H., 1997. Critical time of different humidity and temperature conditions for the development of brown rot decay in pine and spruce. Holzforschung 51 (2), 99–106.
Viitanen, H., Ritschkoff, A.-C., 1991. Mould growth in pine and spruce sapwood in relation to air humidity and temperature. Swedish University of Agricultural Sciences, Department of Forest Products. Report No. 221.
Viitanen, H., Salonvaara, M., 2001. Failure criteria. In: Trechsel, E. (Ed.), Moisture Analysis and Condensation Control in Building Envelopes. American Society for Testing and Materials, West Conshohocken, Pennsylvania, pp. 66–80. ASTM MNL 40.
Viitanen, H., Peuhkuri, R., Ojanen, T., Toratti, T., Makkonen, L., 2008. Service life of wooden materials—mathematical modelling as a tool for evaluating the development of mould and decay. In: Van Acker, J., Peek, R.D. (Eds.), Proceedings of the COST Action E 37 Final conference "Socio-Economic Perspectives of Treated Wood for the Common European Market". COST Action E 37; Sustainability Through New Technologies for Enhanced Wood Durability, Final Conference, Bordeaux, France, 29–30 September 2008.
Viitanen, H., Toratti, T., Makkonen, L., Peuhkuri, R., Ojanen, T., Ruokolainen, L., et al., 2010a. Towards modelling of decay risk of wooden materials. Eur. J. Wood Wood Prod. 68, 303–313.
Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., et al., 2010b. Moisture and bio-deterioration risk of building materials and structures. J. Build. Phys. 33 (3), 201–224.
Viitanen, H., Ojanen, T., Peuhkuri, R., Vinha, J., Lähdesmäki, K., Salminen, K., 2011. Mould growth modelling to evaluate durability of materials. In: XII DBMC International Conference on Durability of Building Materials and Components, Porto, Portugal, 12–15 April 2011.
Vrouwenvelder, A., Schießl, P., 1999. Durability aspects of probabilistic ultimate limit state design. HERON 44 (1).
Vrouwenvelder, A., Vrijling, J.K., 1987. Probabilistisch ontwerpen. Lectures Notes (in Dutch). Civil Engineering, Delft University of Technology, Delft, The Netherlands.
Wang, J., Wu, X., Jiang, M., Morris, P.I., 2007. Decay Hazard Classification in China for Exterior Above-Ground Wood. The International Research Group on Wood Protection, Stockholm. IRG/WP/07-20357.
Wang, C.-H., Leicester, R.H., Nguyen, M.N., 2008. Decay Above Ground. Manual No. 4. CSIRO Sustainable Ecosystems, Urban Systems Program, Highett, Victoria, Australia.

Wilcox, W.W., 1978. Review of literature on the effects of early stages of decay on wood strength. Wood Fibre 9 (4), 252–257.
Williams, R.R., 2005. Weathering of wood. In: Rowell, R.M. (Ed.), Handbook of Wood Chemistry and Wood Composites. CRC Press, Boca Raton, FL.
Winandy, J.E., Lebow, P.K., 2001. Modeling strength loss in wood by chemical composition. Part I. An individual component model for Southern pine. Wood Fiber Sci. 33 (2), 239–254.
WUFI-software. Wärme Und Feuchte Instationär (heat and moisture transiency). https://wufi.de/en/.

Environmental assessment of bio-based building materials

9

E. Suttie[*], *C. Hill*[†,‡], *G. Sandin*[§], *A. Kutnar*[¶,‖], *C. Ganne-Chédeville*[#], *F. Lowres*[*], *A.C. Dias*[**]

[*]BRE, Watford, United Kingdom, [†]JCH Industrial Ecology Ltd, Bangor, United Kingdom, [‡]NIBIO, Ås, Norway, [§]RISE Research Institutes of Sweden, Gothenburg, Sweden, [¶]University of Primorska, Koper, Slovenia, [‖]InnoRenew CoE, Izola, Slovenia, [#]Bern University of Applied Sciences, Biel/Bienne, Switzerland, [**]University of Aveiro, Aveiro, Portugal

9.1 Introduction

The imperative for the construction industry is to drive down the contribution the sector makes to global CO_2 emissions by delivering energy-efficient buildings more efficiently using the lowest impact construction products. Approximately 50% of global CO_2 emissions are associated with the built environment with half coming from the operational impact of buildings such as heating, lighting and cooling and half again embodied through manufacture and processing in the materials and products that are chosen for the construction.

As the deeper- and far-reaching impacts of climate change and global warming became apparent in the 1990s, regulators were motivated in some countries to act and tackle their commitments to the Kyoto Protocol as their targets to reduce carbon emissions became ratified by national governments. Much of the regulation was directed towards the construction industry to build upon platforms already in existence to promote delivery of energy-efficient buildings. In addition, consideration was being given to the material and products that were being selected to create the energy-efficient homes and commercial properties of the future and for the refurbishment of existing building stocks. From the mid-1990s, it was clear that designers and architects had a crucial role in the creation of low-carbon buildings so tools and methods were targeted at them including robust information to enable meaningful sustainability choices to be made at the design stage. Coming to the present day, in 2016, we have a harmonised life cycle assessment (*LCA*) methodology in Europe and a uniform process of delivery of environmental product declarations (*EPDs*) to showcase the sustainability attributes of construction products across Europe.

Considerable discussion around the embodied impacts of construction products and materials focuses on the carbon footprint of the product and its contribution to greenhouse gas (*GHG*) emissions. From the perspective of bio-based construction products and materials, this seems to present an opportunity as the starting point for a bio-based material is the carbon sequestered from the atmosphere to create the material—resulting in a negative-carbon starting point. As this chapter explores, it is not quite that simple as consideration of the whole life cycle impacts needs to be taken into account,

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00009-4
© 2017 Elsevier Ltd. All rights reserved.

a critical phase being the in-service phase—a products fitness for purpose—where premature failure of a material or product will lead to significant additional environmental burdens and a poor LCA outcome.

This chapter considers the environmental assessment of building materials and some examples and features of bio-based materials. The modules of LCA are detailed, and carbon accounting is considered including the unique characteristic of bio-based materials—the carbon sequestered in them. The contributions to the circular economy, bio-economy and low-carbon economy are discussed. There are firmly established and well-recognised methods for measuring environment profiles and labelling products. The labelled products are then considered in the context of how the environmental assessment of buildings is conducted and communicated.

9.2 Environmental assessment of bio-based building materials

9.2.1 Environmental assessment of building materials from processing, use and end of life phase

Several environmental impacts arise along the life cycle of building materials, that is, from raw material supply up to end of life and including manufacturing, construction process and use stages. Although different tools may be used to evaluate those impacts, LCA, which consists of the compilation and evaluation of the inputs, outputs and corresponding environmental impacts of a product throughout its life cycle (ISO 14044, ISO, 2006c), has advantages compared with other tools. LCA addresses both the entire life cycle of a product and a comprehensive range of environmental impacts, resulting in the avoidance of problem shifting, for example, from one life cycle stage to another or from one environmental compartment to another. LCA has been applied to different types of bio-based building materials, such as modified wood (Ferreira *et al.*, 2016; Hill and Norton, 2014), wood-based panels (Rivela *et al.*, 2005; Werner and Richter, 2007; Wilson, 2009; dos Santos *et al.*, 2014; Silva *et al.*, 2013, 2014), corkboards (Sierra-Pérez *et al.*, 2016) and materials based on agricultural (Ardente *et al.*, 2008; Silva *et al.*, 2014) and animal resources (Murphy and Norton, 2008). Nowadays, there are also several EPDs focusing on bio-based building materials. In Europe, most of them follow the EN 15804 (CEN (2012b)) standard that provides core product category rules (*PCR*) for all construction products and services to ensure that the EPDs are elaborated, verified and presented in a harmonised way. This standard is organised in modules (from A to D) and distinguishes four stages within the life cycle of a building product: product stage, construction process stage, use stage and end-of-life stage. The main environmental impacts associated with each stage are presented below for bio-based building materials.

9.2.1.1 Product stage (modules A1 to A3)

These modules give information about raw material supply, transportation and manufacturing. It corresponds to the so-called ‘cradle-to-gate’ assessment, which consider

all flows and activities from the production, harvesting or collection of the raw material to the finished and packed product ready to be transported to the construction site. If recycled products are used as raw material, all processes linked to their manufacturing are also accounted in these modules.

A1: Raw material supply

Bio-based building materials can be made from several resources. Wood is one of the main bio-based materials used in the world, but several other bioresources are also used in construction, for example, bamboo, corn residues or sheep wool. We can separate them in two main categories: forest products and agriculture/animal products. Additionally, additives (mainly glues, coatings and preservation substances) from a bio-based or from fossil sources can be used for producing building materials (e.g. glues for particle boards, matrices for wood-plastic composites or preservatives for impregnated wood). Finally, recycled bio-based material can be used as raw material for bio-based building (e.g. recycled paper or solid wood).

Forest products. For the production of raw materials derived from forests, such as wood, cork or bamboo, a number of operations are carried out during forest management activities that originate environmental impacts (van Dam and Bos, 2004; van der Lugt *et al.*, 2006; Dias and Arroja, 2012; González-García *et al.*, 2013). The burning of fossil fuels in mechanised operations (e.g. cleaning, thinning, pruning or harvesting) generates air emissions such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x), which contribute, for example, to climate change, acidification and formation of photochemical oxidants. Fertiliser application may cause eutrophication due to nutrient release to the environment and can contribute to climate change as a result of nitrous oxide (N_2O) emission to the atmosphere. The application of pesticides may lead to toxicity-related impacts. Other impacts associated with land use may also arise such as changes in soil organic carbon and fertility, biodiversity, erosion and water use. On the other hand, forest ecosystems have the capacity to uptake CO_2 from the atmosphere and store this carbon in living (stemwood, branches, foliage and roots) and dead biomass (litter, wood debris and soil organic matter), which is an environmental benefit.

Agriculture and animal products: Global land use is characterised by competition between food, fuel and feed production. There are higher risks for indirect land-use change (*ILUC*) and the associated environmental impacts for agricultural production. For example, biofuel production typically takes place on cropland, which was previously used for food production. Since this agricultural production is still necessary, it may be partly displaced to previously noncropland such as grasslands and forests. This process is known as indirect land-use change (ILUC). ILUC risks negating the GHG savings that result from increased biofuels because grasslands and forests typically absorb high levels of CO_2 (European Commission, 2012).

Many products from agriculture and livestock husbandry can be used as raw material in buildings. Amongst them are straw, flax, sugar cane bagasse, corn, hemp, rice husk, groundnut shells, kenaf, reed, sheep wool, casein and polylactic acid (*PLA*) (Schmidt *et al.*, 2004; Ardente *et al.*, 2008; Murphy and Norton, 2008; Menet and Gruescu, 2012; Silva *et al.*, 2014; Chaussinand *et al.*, 2015; Palumbo, 2015).

Conventional agricultural processes need fuel, fertiliser and pesticides similar to a forestry processes. Besides this, land use and soil preparation can be intensive and can lead to degradation of the soil leading to natural resources loss. Agricultural processes are responsible for emissions and environmental impacts in the same way as forest products. But for the cultivation of crops, fertilisers, pesticides, fuels and machine, utilisation is higher due to the annual cycles of cultivation. dos Santos *et al.* (2014) showed that the production of bagasse was the most relevant flow for eutrophication in an LCA of particle board due to the utilisation of fertilisers. The same observations were made by Ganne-Chédeville and Diederichs (2015) for the production of PLA contained in ultralight particle boards. Some crops need a high amount of water for irrigation. Intensive use of water for growing crops can lead to reduction of fresh water availability, which accounts as natural resource depletion. To a greater extent, it can also lead to ecotoxicological effects, by concentration of pollutants and biodiversity loss. Some bioresources can be directly collected from nature, for example, reed grass growing naturally in wetlands for roofing thatch. This avoids environmental impacts due to fertilisation and use of pesticides. The environmental impacts of animal hairs, mainly sheep wool, have been extensively assed (Henry, 2012). The major impacts of wool production are methane (CH_4) emissions from sheep farms, which contribute to climate change and water consumption of the wool treatment processes. Other impacts are due to growing of biomass for feeding the sheep (impacts of agricultural products) and the energy and fuels used in the farms and for the wool treatments (mainly CO_2, SO_2 and NO_x emitted). Agriculture and animal production systems have a lot of co-products that are the basis for bio-based building materials. For example, meat and wool are two coproducts of the sheep production system. Environmental burdens of the coproduct are attributed mostly through economical allocation but sometimes also through mass allocation (Biswas *et al.*, 2010; Jones *et al.*, 2014).

Additives. Depending on their composition, manufacturing process and if they are produced out of fossil or bio-based sources, additives can have relevant environmental impacts even if they are used in small quantities. Preservatives are additives often used to extend the service life of bio-based building materials. Oil-borne preservatives such as creosote or water-borne preservatives such as copper or boron-based solutions are common for wood preservation (Hill, 2006). Processes of distillation and pyrolysis go through the combustion of fossil fuels or biomass, contributing to climate change, acidification, photo oxidation and resources depletion. In the case of metal-based preservatives (e.g. copper), raw material collection needs mining activities (loading, hauling, crushing and grinding), which are responsible for abiotic resource depletion, land use as well as air pollution (emissions of particles) and global warming potential due to fuel usage (Norgate and Haque, 2010). The production of petrochemical, mainly synthetic binders and plastics (e.g. urea-formaldehyde, polyurethane, melamine, polyethylene, polyester or phenolic resins), is responsible for fossil resource depletion and often needs high amounts of input energy as fossil fuels, which lead to CO_2 emissions and contribute strongly to climate change (Rivela *et al.*, 2005; Werner and Richter, 2007; González-García *et al.*, 2009; Wilson, 2009; Silva *et al.*, 2014; Sathre and González-García, 2014; Ganne-Chédeville and Diederichs, 2015). On the other side, bio-based additives, for example, tannin (Pizzi, 2008), corn starch, rubber, PLA

(Ganne-Chédeville and Diederichs, 2015), sodium alginate (Palumbo, 2015), proteins, linseed oil or other natural extracts from plants and trees, can be used. Even if they are based on renewable resources, they also need to be grown, harvested (see environmental burdens of forest and agricultural products), processed, extracted or treated, which lead mostly to environmental burdens linked to emissions of energy production and consumption.

Recycled products: Recycled products are interesting alternatives for reducing the environmental impact of raw materials. Only the environmental burden linked to the manufacturing of these products that are not included in the module C3 (waste treatment/preparation for recycling) is to be accounted in an LCA of the products (EN 15804, CEN, 2012b). If the product can directly be reused without transformation (e.g. reuse of a wood beam), no environmental impact should be attributed to the raw material phase. But some products need to be transformed in order to be reused. For example, recycled paper process includes water and chemical consumption, heat and mechanical treatment operations (Arena *et al.*, 2004). This process is responsible for environmental impacts like fresh water depletion, water ecotoxicity, climate change, acidification and photo oxidation.

A2: Transportation from cultivation or production place to product manufacturing place

The magnitude of the environmental impacts derived from raw material transport depends both on the distances travelled and the transport mean (truck, train, ship or airplane). Besides, within each transport mean, variations may occur depending on the optimisation level of the transport and the density of the material transported, which affect the load capacity and also on the fuel type and vehicle technology. In the case of an electric train, it also depends on the electricity production mix in the region. The impacts originate mostly from air emissions (e.g. CO_2, NO_x and particles) not only from fuel combustion but also from the production of capital goods such as road infrastructure and vehicles (Frischknecht *et al.*, 2007).

A3: Manufacturing of product

Manufacturing of the bio-based building materials comprises many steps and may be very different from one product to another. The environmental impacts of three main groups of activities in manufacturing are presented here: common operation, modification treatments and production of bio-based boards.

Common manufacturing steps: Drying, sawing, planning, sanding, gluing and packaging are typical manufacturing processes of bio-based building materials. Drying is one of the critical processes as hot air must be produced through the combustion of fossil fuels and consequently leads mainly to CO_2, SO_2 and NO_x emissions responsible for climate change, acidification and photo oxidation as well as abiotic resource depletion. On the other hand, companies that are producing bio-based materials often use production waste (e.g. sawdust and wood shavings) as fuel for drying. In this closed-loop situation, CO_2 emissions are accounted as biogenic and therefore assumed to be climate neutral in global warming potential calculations. Sawing, planning and

gluing activities need mainly electricity, so that their environmental impact is strongly linked to the electricity mix used in the region. Renewable energy sources (photovoltaic, wind, hydraulic and biomass) can replace fossil fuels (coal, gas and oil) and nuclear sources to reduce the environmental impacts. Although environmental impacts of the infrastructure (capital goods) accounted to the products are commonly neglected, they can substantially contribute to ecotoxicity, fossil resource depletion and climate change (Frischknecht *et al.*, 2007).

Modifying forest products: Bio-based raw material modification for the production of bio-based building materials includes mainly application or impregnation processes and thermal treatment infrastructure (Hill, 2006; Ferreira *et al.*, 2016). Treatment infrastructures comprise typically of a cylindrical pressure vessel (autoclave) often equipped with vacuum pumps and/or an electrically operated heating system. Here also, impacts are depending on the electricity mix used. Substances used in impregnation/modification processes need to be first diluted in water, causing water-resource depletion. Sometimes, leakages can happen during processing, which often lead to water ecotoxicity, depending on the toxicological properties of the substance used and the site environmental management plan. During the modification processes and at the end of the processes, impregnation substances and/or extracted substances due to vacuum and heat treatment are released into process liquids. Those can be problematic wastes and need to be treated. For impregnation processes, it is mostly possible to reuse the preservatives or chemical again for a next impregnation cycle. For thermal treatment, the residue present in the process water should be concentrated and the waste water treated, which requires electricity. Finally, the residues must be recycled. If this is not possible, they are landfilled, which lead to land use and, depending on their composition, ecotoxicological impacts in soil and water compartments.

Producing bio-based boards: Environmental impacts associated with the production of bio-based boards (particle board, medium density fiberboard (*MDF*), oriented strand board (*OSB*), light density fiberboard (*LDF*) and plywood) and insulation boards arise during the combustion of fuel for hot pressing and as the consumption of electricity as veneers, particles or fibres is prepared and the boards are finished (sanding) (Rivela *et al.*, 2005; Werner and Richter, 2007; González-García *et al.*, 2009; Wilson, 2009; Silva *et al.*, 2014; Sathre and González-García, 2014; Ganne-Chédeville and Diederichs, 2015). Corkboards are either cork agglomerates made up with cork granules bound by adhesives such as polyurethane, melamine or rubber (called composition or white cork agglomerates) or cork agglomerates exclusively made of cork where the cork granules are thermally self-bonded (called pure expanded or black cork agglomerates). The environmental impacts of manufacturing are usually higher in the production of the first type of corkboards, mainly due to fossil fuels used for thermal energy production, which are not required in the case of expanded cork agglomerates (Pargana *et al.*, 2014; Sierra-Pérez *et al.*, 2016). Some insulation boards include, in addition to the common steps of board manufacturing, a foam-expansion step using blowing agents (e.g. chlorofluorocarbons, pentane or liquid CO_2), which are released into the environment (Ganne-Chédeville and Diederichs, 2015). Depending on their properties, they can have more or less contribution to climate change, ozone depletion or human toxicity. Bio-based board containing formaldehyde or isocyanates can, through the release of these compounds during the

manufacturing, lead to human toxicity impacts (He *et al.*, 2012). Finally, some bio-based boards have an extrusion step (e.g. wood-plastic composites), which is energy-intensive for which environmental impacts are directly linked to the electricity mix in the region.

9.2.1.2 Construction stage (modules A4 to A5)

These modules give information about product transportation and installation processes as part of the building. They also include processing and disposal of generated wastes (e.g. 'cut to fit on site' waste and packaging waste) during the installation process. The impacts from the product transportation are similar to those associated with raw material transportation, as referred above. Not only the impacts from the installation processes may include some on-site impacts mostly related to air emissions but also the impacts from the production of energy and ancillary materials used. The impacts from waste management greatly depend on the type of materials and processes involved. Kellenberger and Althaus (2009) found that, in general, the impacts from transport and production of ancillary materials (joints, connectors, etc.) may be significant, whilst the impacts from the building process and cutting waste were less significant.

9.2.1.3 Use stage (modules B1 to B7)

These modules give information about the environmental impacts due to the use, maintenance, repair, replacement and renovation of the building fabric, as well as to the operation of the building, mainly related with energy and water flows. When bio-based materials treated with preservatives are used outdoors, leaching processes may take place with the release of chemicals to terrestrial and aquatic environments, causing toxicity-related impacts (Hingston *et al.*, 2001). Also, formaldehyde and other volatile organic compounds (*VOCs*) may be emitted during the use of bio-based materials incorporating adhesives or coatings, both outdoors and indoors (Roffael, 2006). These emissions are particularly impactful indoors, where they are recognised as causing multiple effects on human health, comfort and productivity. The impacts from maintenance, repair, replacement and renovation result mainly from the consumption of energy, water, components (e.g. door and window) and ancillary materials (e.g. paints and varnishes), as well as from the management of produced wastes and transport of components, materials and wastes. The magnitude of these impacts depends on physical building characteristics such as applied building services and material lifespan, as well as other factors such as the rate of deterioration and maintenance activities (Blom *et al.*, 2010). The operational impacts of the building usually dominate the cradle-to-grave impacts mainly due to the high-energy consumption to satisfy heating, air conditioning, electricity requirements and hot water production (Bribián *et al.*, 2009; Gustavsson *et al.*, 2010). Though it is worth noting that as buildings become more energy efficient, the embodied energy of the products used to build or refurbish the building becomes proportionally more significant as the lifetime operational energy reduces. However, in some cases, buildings incorporating higher proportions of bio-based products normally have lower environmental impacts during the use stage as they require less energy (Bribián *et al.*, 2011; Pajchrowski *et al.*, 2014).

9.2.1.4 End of life stage (C1 to C4)

These modules contain all processes for the deconstruction, transport to waste treatment, preparation for recycling and/or final disposal. For deconstruction, mainly fossil-fuel-powered machines are used. The environmental impacts of the transport to the waste treatment place depend on the level of optimisation of the transportation system, the distance to the elimination place, the type of transportation and the density of the material. Lighter materials will cause less fuel consumption during transport (Murphy and Norton, 2008; Ganne-Chédeville and Diederichs, 2015). Preparation for recycling can contain diverse processes like crushing, selecting or digesting, which needs electricity and can release GHGs. In most cases, bio-based materials are disposed of through incineration for energy recovery where they release combustion gases, resulting in impacts like acidification, eutrophication, climate change and photo oxidation. Products containing fossil-based additives (e.g. urea-formaldehyde glue) will release fossil CO_2, contributing to climate change. Depending on the type of incineration system, other gases and particles can be released, causing ecotoxicity and human toxicity. Municipal incineration of bio-based building material often leads to low environmental performance due to the specific burdens of the incineration systems and because the materials are mixed with nonbio-based materials. Wastes from incineration need to be landfilled, which cause impacts in the categories of land use, soil ecotoxicity and climate change. Benefits of energy recovery from bio-based material incineration, avoiding the utilisation of fossil fuel for heat and electricity generation, are declared in the informative module D (benefits and loads beyond the product system boundary). If system expansion is applied (module D considered in the system limits), this leads often to a drastic reduction of the global warming potential of the product. Finally, the product can be directly landfilled, which has as a main consequence an impact in land use and, depending on its composition, ecotoxicity in soil and water as well as climate change due to methane and CO_2 released during decay processes. However, the anaerobic decay of some materials like wood, cork or paper is incomplete leading to long-term carbon storage in landfills (De la Cruz *et al.*, 2013).

9.2.2 Carbon accounting

Anthropogenic GHG emissions are making a substantial contribution to climate change (Intergovernmental Panel on Climate Change (*IPCC*), 2013). Since preindustrial times (before 1750), the concentration of carbon dioxide in the atmosphere has risen from a baseline level of 280 ppm (parts per million) to over 400 ppm at present. When the global warming effects of the other GHGs (primarily methane and nitrous oxide) are also taken into account, the level is around 450 ppm of carbon dioxide equivalents (CO_2e). Levels of GHGs are presently higher than they have been for any time in the past 800,000 years. These contributions to the increase in atmospheric CO_2 concentration since the industrial revolution come mainly from the combustion of fossil fuels, gas flaring and emissions associated with cement production. Other sources include deforestation, land-use change and biomass burning (contributing about 20%) (IPCC, 2007). Although the atmospheric GHG levels continue to increase, there are

various natural processes by which atmospheric carbon dioxide is removed from the atmosphere. These are the following:

- photosynthetic production of biomass (terrestrial and aquatic)
- weathering of silicate rocks
- dissolution in the oceans

If all human additions of carbon dioxide to the atmosphere were to cease immediately, the atmospheric concentration would gradually return towards preindustrial levels. About 50% of the increase above the background level of 280 ppm would be removed in 30 years. This is assuming that anthropogenic interference in the climate does not lead to irreversible effects, such as melting of methane clathrates or oxidation of peat. The IPCC (2013) agrees that 'most aspects of climate change will persist for many centuries even if emissions of CO_2 are stopped' and that in human timescales a large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible with 15%–40% of emitted CO_2 remaining in the atmosphere for over 1000 years.

The management of carbon in the biosphere differs from fossil carbon management in that carbon can both be emitted from and sequestered to the biosphere. Whether there is a net radiative forcing, cooling or equilibrium depends on the balance and timing of the release and sequestration of the biogenic carbon. The amount of carbon stored in the living biomass of the planet totals up to 600–1000 Gt of carbon, with something of the order of 1200 Gt being locked up in dead biomass. Most of the carbon of the terrestrial biosphere is stored in forests, which contain about 86% of the above-ground biogenic carbon and 73% of the carbon stored in the soil. Due to the activities of humanity, these carbon pools are reducing in size; carbon stocks in global forests are decreasing by 1.1 Gt/year. However, in most of the countries of Europe, the forest utilisation rate (fellings as a percentage of the annual increment) is <100%, meaning that the carbon pool in European forests is increasing in size. With the current rate of timber harvesting in Europe, forests will move into older age classes, and the net increment of wood material will consequently decline (Nabuurs *et al.*, 2002). This provides an opportunity for increasing fellings to improve the carbon sequestration potential of forests. Furthermore, the utilisation of harvested wood products (*HWPs*) in long-life products also allows for the carbon storage benefits of timber to be extended beyond the forest. The use of biomass in the built environment represents a stable and easily accountable way of storing atmospheric carbon for long periods of time, creating a new carbon pool. Furthermore, the substitution of other building materials that often have a higher carbon footprint brings additional benefits. The question is how can this carbon storage benefit be measured and reported?

Carbon accounting refers to processes used to measure and track the flows of carbon atoms through technological systems and how these interact with the environment. Methodologies for carbon accounting are assuming greater importance due to concerns regarding the impact of the release of fossil carbon into the atmosphere, primarily as carbon dioxide and methane. It is an essential element of carbon-trading schemes, such as the European Union Emissions Trading System, and it is also needed in order to report on national GHG inventories required under the Kyoto

Protocol. Carbon accounting can also be used as a means of supporting informed decisions about products and processes, using LCA methodologies; these are sometimes referred to as carbon footprints. Carbon-trading schemes have been introduced to internalise the external costs of carbon emissions and are a means by which countries are able to meet their obligations under the Kyoto Protocol. The EU launched a carbon-trading scheme in 2005, covering power plants, aviation and energy-intensive industries. There are various carbon-trading schemes around the world, but there is no global trading scheme at present. In a future carbon-trading market, it is envisaged that carbon credits could be given for the storage of atmospheric carbon (as biogenic products) in buildings. The value placed upon the storage of atmospheric carbon should be represented in the market. For example, credits could be given for the use of timber in construction, an idea that requires deep scrutiny in the context of existing methodologies for assessing the sustainability of construction products and buildings. The storage of atmospheric carbon is an important component of a bio-based construction product life cycle, but equally, other questions need addressing: How long the carbon will be stored? What happens to the carbon at the products end of life?

The role of HWPs in mitigating GHG emissions has only recently been recognised by the Kyoto Protocol. For the first commitment period (2008–12), it was assumed that the quantity of carbon leaving the HWP pool every year was equal to the annual inflow. For the second commitment period (2013–20), the carbon accounting can now include carbon stock changes in the HWP pool. Although the IPCC recognises the importance of the built environment, its mitigation strategies listed in the fourth and fifth assessment reports (IPCC, 2007, 2014) are almost exclusively concerned with energy consumption. The use of wood as an example of a low-embodied-energy material is mentioned, but there is no consideration given to the potential for timber and other plant-derived products to act as carbon stores in the built environment. Furthermore, the use of mitigation strategies associated with forestry is only concerned with bioenergy and does not discuss the carbon storage potential of timber products. However, the Conference of the Parties to the Kyoto Protocol in Copenhagen in 2009 did recognise the importance of including timber products as carbon sinks, and the 2011 Durban and 2012 Doha conferences stated that carbon stored in wood products should be integrated into reporting procedures.

The environmental benefits of using timber as a substitute for high-embodied-energy construction materials have been demonstrated (e.g. Buchanan and Levine, 1999; Börjesson and Gustavsson, 2000; Gustavsson and Sathre, 2006; Nässén *et al.*, 2012). The advantages of using timber and other bio-derived materials as a means of storing sequestered atmospheric carbon in the built environment have also received attention in the scientific literature (e.g. Pilli *et al.*, 2015). Although the environmental benefits of using natural materials, such as timber in construction, can be clearly demonstrated, the same cannot be said for the economics unless the external costs of climate change are internalised into the material prices. This requires carbon accounting methods to be developed (Sathre and Gustavsson, 2009). Conventional LCA methods do not assign any benefits to the temporary storage of atmospheric carbon because the timing of emissions relative to removals is not considered.

But the impacts of storing atmospheric carbon dioxide are dependent upon the length of time for which the carbon is removed from the atmosphere (Cacho *et al.*, 2003; Levasseur *et al.*, 2013). This has been taken into consideration in the UK Publicly Available Specification 2050 (*PAS* 2050, BSI, 2008) and the European Commission's International Reference Life Cycle Data (*ILCD*) Handbook (Wolf *et al.*, 2012). With PAS 2050, the benefits of carbon storage are calculated based on a weighted time average approach for an assessment period of 100 years. For example, if a bio-derived product containing 1 kg of atmospheric carbon is used in a building for 50 years before disposal by incineration, then the benefit of carbon storage is calculated as $(50/100) \times 1 = 0.5$ kg. The ILCD methodology considers biogenic carbon sequestration as a negative value and emissions as a positive value. The carbon credits in biogenic materials arise from the effect of delayed emission over a 100-year assessment period. If the emission of 1 kg carbon is delayed for a period of 50 years, this is calculated as $(50/100) \times 1 = 0.5$ kg, in the same way as the PAS 2050 example. The benefits of atmospheric carbon storage in bio-derived products can only be accounted for if the material is derived from a sustainable production source. For the case of timber products, this means that there has to be regeneration of the forest after felling to produce the timber. If felling of the timber results in land-use change (such as conversion to agriculture), then the benefits of atmospheric carbon storage in the HWPs are no longer present, and according to the ILCD guidelines, this biogenic carbon should be treated as if it was fossil carbon. Brandão *et al.* (2013) reviewed six methods (including PAS 2050 and ILCD) for accounting for the impacts of carbon sequestration and the temporary storage and release of biogenic carbon. The paper identified that the benefits of carbon storage are highly dependent upon the time horizon adopted and that this is based upon value judgements rather than having any sound scientific basis. As such, the timeframe adopted is informed by policy considerations, and the commonly used 100-year period for global warming potential (*GWP*) calculations is based upon the desire to bring about achievable change in a crucial period in the history of humanity. The intention is to change behaviour to a sustainable development trajectory.

Although many studies of carbon storage in HWPs have been conducted, there are no commonly recognised methods for determining and reporting this in bio-derived products from a time perspective. PAS 2050 and ILCD give two methods for dealing with the temporal factor, but other approaches have been suggested. The method of Moura-Costa and Wilson (2000) calculates a sequestration-based equivalence factor called the absolute global warming potential (*AGWP*). The AGWP is defined as the cumulative radiative forcing potential for CO_2 of unit mass over a specified time horizon. This is calculated from the following relationship:

$$\mathrm{AGWP} = \int_0^{\mathrm{TH}} a_x \cdot \left[C(t)\right] \mathrm{d}t \tag{9.1}$$

where *TH* is the time horizon under consideration, t is time, a_x is the radiative forcing due to the presence of unit mass of CO_2 in the atmosphere and $C(t)$ is the concentration of a pulse of CO_2, decaying as a function of time, which is usually expressed in terms of the Bern model. Based upon these considerations, they found that removing 1 tonne of CO_2e from the atmosphere and storing it for 55 years counteracts the effect

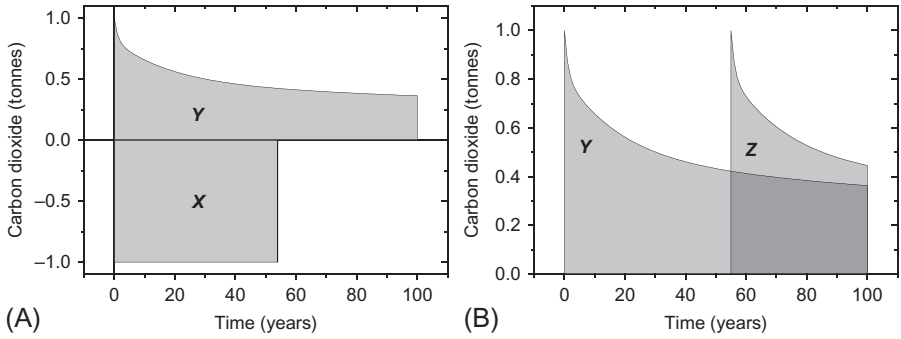


Fig. 9.1 Illustration of the Moura-Costa (A) and Lashof (B) methods for calculating the benefit of carbon storage. In (A), a pulse of 1 tonne of carbon dioxide is released into the atmosphere, and this decays according to the Bern mechanism. The total global warming potential (GWP) over 100 years is represented by the area under the curve. The same total GWP is represented by storage of 1 tonne of CO_2 for 55 years ($X = Y$). In (B), the carbon is stored for 55 years and then released as a pulse of CO_2. The total GWP is the area under the curve Z; the benefit of storage is given by subtracting Y from Z.

of releasing a pulse of CO_2 into the atmosphere with a residence time of 100 years. This method allows for benefits greater than 100% if the 55-year storage period is exceeded. Another approach, referred to as the Lashof method, assumes that the storage of atmospheric CO_2 is equivalent to a delayed emission of fossil CO_2, but the carbon tracking is performed in the atmosphere rather than the biosphere (Fearnside, 2002; Fig. 9.1).

Levasseur *et al.* (2013) examined the problem of GWP impact using a traditional LCA approach without including sequestered carbon, a traditional approach including sequestered carbon, PAS 2050, ILCD and dynamic LCA methodologies. Each approach gave different results, there were dramatic differences in some cases. It was concluded that the dynamic LCA approach was the preferred method for providing reliable data, although the results obtained were heavily dependent upon the assumptions made and the time horizon considered. The study also examined the problem using a functional unit of a wooden chair, which can give different results compared with studying temporal carbon storage of a pool of HWPs. A pool of biogenic carbon products does not release carbon to the atmosphere in a pulse, as is the case with a single product, but in a manner that is better modelled as a probability distribution (Shirley *et al.*, 2011). Many studies investigating the release of carbon from HWP pools have modelled this behaviour as a single-exponential decay (as in the IPCC guidelines), but Shirley *et al.* (2011) pointed out that this does not adequately consider that the probability of a product being taken out of service is related to the age of that product. This was dealt with by the development of a distributed decay model (Marland and Marland, 2003; Marland *et al.*, 2010), which uses a probability distribution to determine how much of production from a particular year decays in any given time interval. This type of model is analogous to the approach adopted by the life assurance industry in actuarial mathematics. This form of modelling is very useful when attempting to

adopt a realistic methodology for pricing carbon and assigning a value to the cost of emissions from the HWP pool in the future.

The carbon pool of HWPs can be in one of three states, stable, increasing or decreasing. Which one of these applies obviously depends upon the rate at which harvested wood enters the pool and the rate that the carbon in the pool is oxidised. Although a huge amount of atmospheric carbon is stored in wood products, this is of no significance from the point of view of mitigation if the carbon stock is stable. Indeed, the assumption that wood is immediately oxidised after harvesting is mathematically identical to a stable stock of HWPs. If the size of the pool is decreasing, then this means that more biogenic carbon is being released than is entering, which will result in an increase in atmospheric radiative forcing, as is the case with the burning of fossil fuels. From this perspective, it is irrelevant whether the source of the carbon is biogenic or fossil; it is the fact that the stock in the HWP pool is decreasing that is important. Conversely, an increase in the size of the GWP pool is of benefit, since this results in a net sequestration of atmospheric carbon, provided the amount of carbon stored in the forests from which the wood is derived either is stable or is increasing. This means that the timber has to come from sustainably managed forests. The HWP pool size can be increased by raising the amount of wood harvesting and/or by increasing the lifespan of wood products in the HWP pool (increased levels of recycling, improved durability, etc.). The best overall strategy is to increase the level of HWPs and other biogenic materials in the pool as well as increasing the retention time through extending the life of products (enhanced durability) and by adopting a cascade material management structure. Finally, the biogenic carbon can be returned to the atmosphere by incineration with energy recovery, thereby obtaining credits for substituting a fossil fuel source.

This section has considered how the various methods account for the temporal carbon dynamics, and there is also a section focusing on the single product versus the pool perspective. In addition, it is noted that the influence of the choice of spatial system boundaries and the land-use baseline or land-use reference system is of importance in carbon accounting studies. There is insufficient scope to review this topic thoroughly, and readers are directed to multiple authors on this topic (Cherubini *et al.*, 2013; Berndes *et al.*, 2013; Soimakallio *et al.*, 2015; Brander, 2015; Røyne *et al.*, 2016; Penaloza *et al.*, 2016).

Unfortunately, at the time of writing, the situation regarding the methodology of measuring and accounting for carbon in biogenic products is not satisfactory. Although the ILCD methodology is still current, there have not been many useful developments in standardisation. Although the 2008 version of PAS 2050 did include methods for calculating the temporal aspects of biogenic carbon storage in annex C, by the time that the 2011 version had been published, this was no longer present. The European Standard EN 16485 (CEN (2014b)) giving product category rules (PCR) for round and sawn timber featured a temporal calculation method for determining the storage of biogenic carbon in the draft form, but in the final published version, this had been removed. This is a situation that cannot be allowed to continue and urgent action is required.

9.2.3 Circular economy, bio-economy, and low-carbon economy

The expectations and needs of increasingly bio-based building materials are part of a greater transition of our society towards a more bio-based one. In recent years, this endeavour has been embodied in and gained momentum through the emergence of concepts such as 'circular economy', 'bio-economy' and 'low-carbon economy'. The emergence of these concepts is, for example, shown in their increased use in the scientific literature in the past 10 years (Fig. 9.2). Below, we introduce these concepts and discuss how they relate to bio-based building materials.

9.2.3.1 Circular economy

An early notion of the need for a circular economy was that of Kenneth E. Boulding in his essay 'The economics of the coming spaceship Earth' (Boulding, 1966). Boulding argues that economists ought to increasingly treat the Earth as a closed system—thus his analogy between humanity and a spaceman living in a spaceship—in contrast to an open system for which he uses the analogy of a cowboy, which has 'illimitable plains' at his disposal. In a closed system, 'the outputs of all parts of the system are linked to the inputs of other parts' (Boulding, 1966). He recognises that economists at the time, however, viewed the world as an open system in which matter, energy and information are seen as entering the system from somewhere else (i.e. there is a seemingly endless supply of natural resources) and leaving the system to somewhere else (i.e. there is a

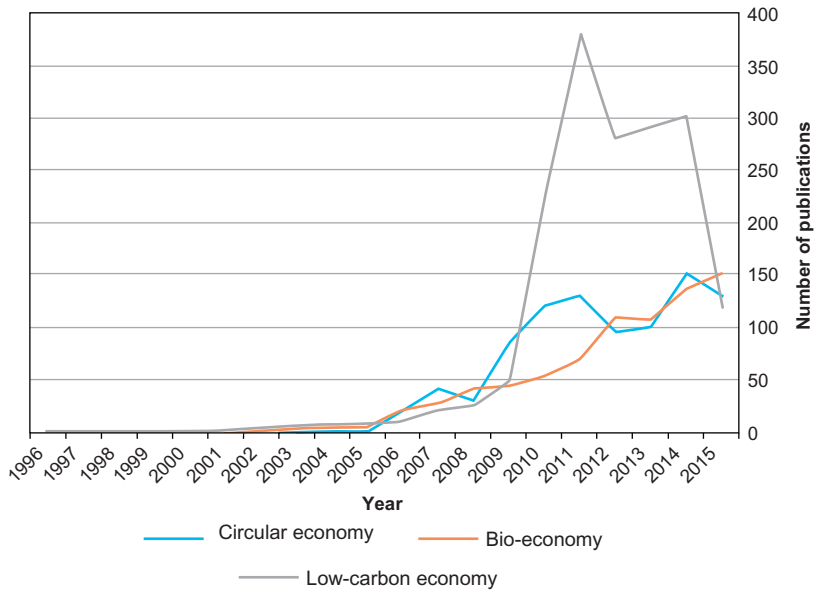


Fig. 9.2 Number of publications found in a search amongst article titles, abstracts and keywords, in the Scopus database of peer-reviewed literature, 5th of Mar. 2016, using the keywords 'circular economy'; 'bio-economy', 'bioeconomy', 'bio-based economy' or 'biobased economy'; and 'low-carbon economy' or 'low carbon economy'.

seemingly endless capacity to absorb waste). He concludes that 'the closed earth of the future requires economic principles which are somewhat different from those of the open earth of the past' in which 'man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy'. This is precisely the idea of the circular economy: closing the material loops within the Earth system, so that waste is used as an input to new productive processes, directly between human activities or via natural processes—for example, CO_2 emissions from incineration of bio-based materials are absorbed by growing biomass, which then is harvested and incorporated in new materials—fuelled by the only abundant energy flow entering the Earth system, solar radiation (directly or via air and water moving because of solar radiation). This is in stark contrast to the still prevailing 'linear' economy, also referred to as a 'take-make-waste' economy.

Although the circular economy concept has been present in the literature since Boulding's work in 1966 (Stahel and Reday-Mulvey, 1981; Pearce and Turner, 1989), it has not received widespread attention until the recent years, as sustainability issues associated with the predominant linear economy have become increasingly apparent. Two developments have particularly put the circular economy in the spotlight. The first was when China adopted circular economy as a development strategy in 2002 (Yuan and Morgiguchi, 2008) and then made it part of its national policy in the 11th five-year plan issued in 2006 (Zhijun and Nailing, 2007). This explains the increase of scientific publications on the topic starting in mid-2000 (see Fig. 9.2; the Chinese context is a remarkably common theme for many of the publications found in the literature search).

The second development that notably increased the interest in the circular economy concept is when the solo long-distance yachtswoman Ellen MacArthur in partnership with five multinational corporations launched the Ellen MacArthur Foundation in 2010. The charity foundation declared a mission to 'accelerate the transition to a circular economy' and developed the first coherent framework around the concept (Ellen MacArthur Foundation, 2015). In the recent years, this framework has shaped discussions in industry and media pertaining to the circular economy. The framework defines a circular economy as 'a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields and minimises system risks by managing finite stocks and renewable flows' (Ellen MacArthur Foundation, 2015). Furthermore, the framework emphasises that, in a circular economy, all energy flows should be renewable and material flows belong to either one of two types: biological nutrients (i.e. biotic materials designed to enter the biosphere safely) and technical nutrients (i.e. materials that are designed to circulate in the technosphere without entering the biosphere). Also, the framework emphasises the importance of managing stocks of materials by sharing, reusing, remanufacturing and recycling, and the importance of managing renewable material flows by preserving and enhancing natural capital (e.g. soil quality) and by cascading (i.e. using a given resource for several subsequent functions before it re-enters the biosphere). Finally, the framework emphasises the need for 'revealing and designing out negative externalities', further described as 'reducing damage to human utility, such as food, mobility, shelter, health, …', and managing land use; air, water and noise pollution; release of

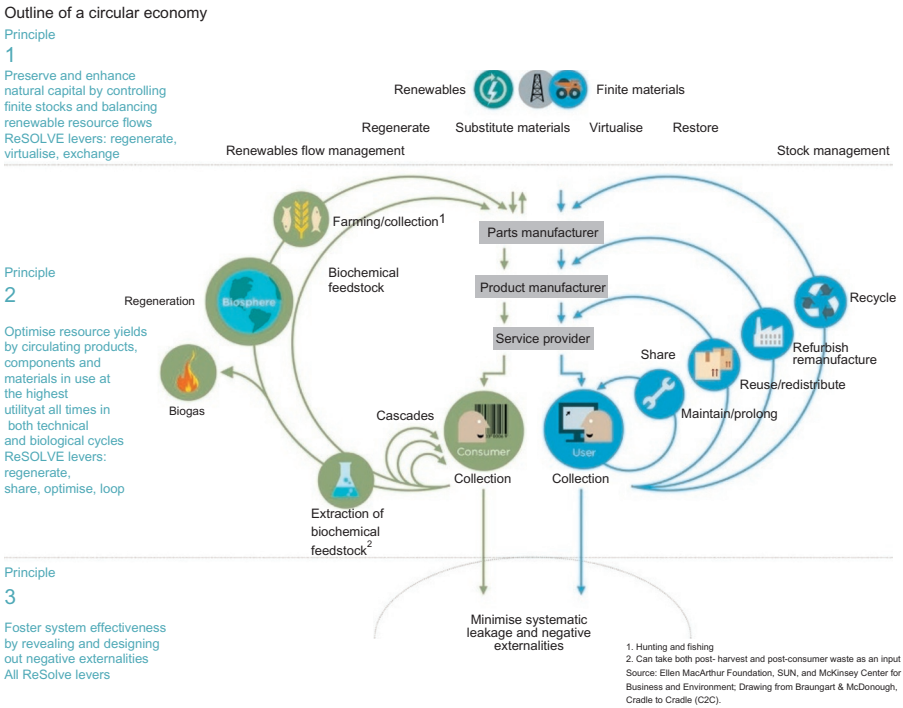


Fig. 9.3 Outline illustration of the circular economy.
Reproduced with permission from the Ellen McArthur Foundation.

toxic substances; and climate change (Ellen MacArthur Foundation, 2015). Fig. 9.3. summarises the building blocks of the circular economy framework as defined by the Ellen MacArthur Foundation.

Cradle-to-cradle (*C2C*) certification of products is connected to the term circular economy as one of the material quality categories is material reutilisation alongside material health, renewable energy and carbon management, water stewardship and social fairness.

For further reading about the circular economy, we recommend the literature review by CIRAIG (2015). Amongst others, the review reveals the connections between circular economy and other, associated concepts, such as the green economy, life cycle thinking and industrial ecology.

9.2.3.2 Bio-economy

As seen in Fig. **9.2**, the concept of a bio-economy (also referred to as a bio-based economy) has also gained momentum in the scientific literature in the past 10 years, most probably because the replacement of fossil resources with bio-based resources is seen as an important means for reducing GHG emissions and dependencies on imported, fossil resources. It has been said that 'the bio-based economy can and should be to the 21st century what the fossil-fuel-based economy was to the 20th century' (Hardy, 2002).

The intention of transitioning to a bio-economy is present also in the political arena. For example, in 2012, the European Commission adopted a bio-economy strategy as a means for addressing the environmental, energy, food supply and natural resource challenges that Europe and the world are facing (European Commission, 2012). In the strategy, the bio-economy is defined as 'the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy'. The European bio-economy strategy has, amongst others, strongly influenced the EU framework for funding research and development, Horizon 2020 (European Commission, 2016). In addition, national bio-economy strategies have been developed, for example, in the United States, Canada, Australia, South Africa, Finland, Germany and Sweden (Ingrao *et al.*, 2016). The Swedish strategy for a transition to a bio-economy is described in the following way: 'the conversion to a bio-based economy entails switching from an economy largely based on fossil resources to a more resource-efficient economy based on renewable resources that are produced through using sustainable soil- and water-based ecosystem services' (VINNOVA, 2013). The term bio-economy is not, however, as prevalent in political and strategic documents as one might think. This is seen in the background material to the report 'The use of concepts related to sustainable development in political and strategic documents' (Fahnestock, 2016a) in which the prevalence of 217 concepts in 110 documents was assessed, and 'bioeconomy' was ranked as the 199th most frequently used concept with only 14 mentions (Fahnestock, 2016b).[1] It should be noted that the term bio-economy often refers to different things in Europe and in the United States: In Europe, it is a very broad term, as described above, whereas in the United States, the term often refers more specifically to the increased use of synthetic biology in society (Scarlat *et al.*, 2015).

Compared with the Ellen MacArthur Foundation framework for a circular economy, the bio-economy is much less of a complete concept in terms of being a comprehensive solution for addressing environmental concerns. Just increasing the use of biological resources does not guarantee a more sustainable society. Therefore, the development of a bio-economy must be combined with careful consideration of the many pressures threatening ecosystems worldwide—which are at risk of being harmed by increased harvesting of bio-based resources—including unsustainable land and water management practices and the subsequent impact on biodiversity. Some policy frameworks advocating a bio-economy do include such consideration as an inherent part of the definition of a bio-economy (e.g. the above definition in the Swedish national strategy), whereas others do not. It should be noted that this previously has been the case also for the circular economy concept, which, through the development of the Ellen MacArthur Foundation framework, was made more coherent and comprehensive, addressing not only material and energy use but also other concerns. Because of the narrow focus on the use of bio-based resources, the bio-economy can be interpreted as a subset of the circular economy.

[1] In the studied documents, 'low carbon' is the 69th most frequently used concept, with 887 mentions, and 'circular economy' is the 129th most frequently used concept, with 175 mentions.

9.2.3.3 Low-carbon economy

The concept of a low-carbon economy (also referred to as a decarbonised economy) has emerged as a means for addressing climate change. A low-carbon economy is simply an economy that causes low levels of GHG emissions compared with today's carbon-intensive economy. 'Carbon' refers to carbon dioxide, the GHG, which contributes the most to climate change. The low-carbon economy can be seen as a step in the process towards a zero-carbon economy.

Just as the bio-economy, the low-carbon economy is a narrow concept compared with the circular economy concept, as its coverage is limited to one parameter of a future sustainable society. In contrast to the bio-economy, the low-carbon economy is, however, more focused on reducing environmental impact rather than on promoting a certain solution for achieving the reduction. That is, the low-carbon economy is rather a goal than a means or strategy for reaching the goal. Both the bio-economy and the circular economy concepts give more guidance for how to reach goals. This difference is reflected in policy frameworks. For example, the European Commission has set a goal to develop a low-carbon economy by 2050, a development in which the bio-economy is expected to play a significant role (Scarlat *et al.*, 2015).

9.2.3.4 Circular economy, bio-economy and low-carbon economy in relation to bio-based building materials

From the above descriptions, it is clear that bio-based building materials are potentially an important component in the circular economy, bio-economy and low-carbon economy. In particular, bio-based building materials are by necessity a fundamental part of a bio-economy, considering that building materials represent such a large share of the materials produced and used in society—about 40% (Roodman and Lenssen, 1995). It is also difficult to envision a low-carbon economy without a substantial share of bio-based building materials, as such materials in general give rise to lower GHG emissions compared with other, functionally equivalent building materials (Werner and Richter, 2007; Salazar and Meil, 2009; Pajchrowski *et al.*, 2014). Although such comparisons to some extent depend on the chosen assessment method and uncertain parameters in the material life cycle, studies indicate that bio-based materials are often a preferable choice even when such aspects are accounted for (Sandin *et al.*, 2014; Røyne *et al.*, 2016).

Increased use of bio-based building material is probably also important for developing a circular economy, although abiotic materials may play a greater role in such an economy compared with a bio-economy or a low-carbon economy. However, for bio-based building materials to be part of a circular economy, it is important that (i) the material origin from regenerative agricultural or forest land managed in a way that avoids negative externalities; (ii) land management, harvesting and further processes in the material life cycles are fuelled by renewable energy and (iii) the materials are designed in a way that allows them to safely re-enter the biosphere at their functional end of life, which means that biological and technical nutrients that are combined (e.g. in composites) must be possible to separate and that toxic substances (e.g. used for preservation or fire protection purposes) must be degraded at end of life (e.g. through incineration).

9.3 Measurement and certification

To provide clarity to enable informed choices to be made of low-impact construction materials and products, it is essential to have a robust and consistent means of measuring, attributing impacts and certification of the construction products and the construction assets lifecycle environmental impacts.

9.3.1 Environmental profiles and eco-labels

9.3.1.1 Different types of eco-labels

Environmental labels are an internationally recognised means of communicating the environmental credentials of products in response to consumer demand for information. Different labels take different assessment approaches, but the common goal is to present verifiable and accurate information and to promote products and services that have potentially less impacts on the environment by aiding buyers to make better informed choices. Environmental labels are voluntary and are developed under the ISO 14020 (ISO (2000)) series of standards and fall under three classes: Type I, Type II and Type III, with the series of standards setting out the guiding principles for the development of environmental labels and declarations (Allison and Carter, 2000).

This section provides a short description of each of the three different types of labels, the standards they are related to within the ISO 14020 (ISO (2000)) series and examples of how these labels apply to bio-based products, with particular focus on Type I and Type III environmental labels. Drivers for the use of these labels are also provided in this section.

Type I—Ecolabels

This is an environmental label established under the requirements of ISO 14024 (ISO (2004)). Type I labels are based on a pass-fail multicriteria approach devised to indicate the overall environmental performance of a product. If one of the criteria is not met, the product will not be awarded a label. Commonly referred to as 'eco-labels', Type I environmental labels are provided by programmes set up and operated in line with the requirements of ISO 14024 (ISO (2004)). Eco-labels are third-party verified and are typically simple documents that convey basic relevant environmental information. Many national eco-labels have evolved with at least 40 being actively used on construction products across the globe from Israel to India and Hong Kong to Hungary.

Type II—Self-declared environmental claims

Type II environmental labels are defined as 'self-declared' environmental claims made by manufacturers and businesses. Guided by ISO 14021 (ISO (2016)), the claimant can declare the environmental quality of their product, without set criteria, nor benchmarks, nor quality checks. However, this declaration should be verifiable and must not be misleading. Other restrictions include the avoidance of vague or ambiguous claims such as 'environmentally friendly' or 'more sustainable'. Verifiable terms such as 'made from x% recycled material' are permitted.

Type III—Environmental declarations based on LCA

Referred to as EPD, Type III environmental labels are defined by ISO 14025 (ISO (2006a)) and are third-party verified under established programmes. Prepared from LCA using predetermined criteria-set rules, EPD are typically more complex compared with eco-labels as they contain a range of information from various aspects of the product supply chain. Type III labels are comparable with nutritional labels on food products and can be used for product comparison under strict guidelines dictated by relevant standards. Type III labels for construction products are further governed by specific standards at both the international and European level (ISO 21930, ISO, 2007; EN 15804, CEN, 2012b, respectively), and the LCA studies are according to the ISO 14040 (ISO (2006b)) series of standards. Type III labels are best suited to communicating environmental credentials of products to businesses or public bodies, because they give more comprehensive information on a product than Type I and Type II, and the outputs have been interpreted.

9.3.1.2 Type I—Ecolabels

Examples of the main ecolabels

Blue Angel (2013) is the first worldwide eco-labelling system. Created in 1978 on the initiative of the German Federal Minister of the Interior, the Blue Angel predates the ISO standard for Type I eco-labelling standard and now covers around 12,000 products and services in more than 100 product categories. Criteria are developed for each individual product group, which must be fulfilled to be awarded with the Blue Angel mark. The requirements set by the eco-label focus on the impacts that products have on the climate, resources, water, soil, air and people. The label is owned by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety.

The Nordic Ecolabel (also referred to as the Nordic Swan) is the official eco-label of the Nordic countries (Iceland, Norway, Sweden, Finland and Denmark). It was introduced in 1989 by the Nordic Council of Ministers to support a more sustainable production and consumption. Currently there are 63 product groups within the Nordic Ecolabel, each with their own set of criteria but considering the same important environmental issues (energy usage, climate aspects, water usage, source of raw materials, use of chemicals, hazardous effluents, packaging and waste).

Introduced in 1991, NF environment is the French eco-label scheme. It is issued by AFNOR Certification (part of AFNOR Group) or a certification body mandated by AFNOR Certification. In order to be awarded this eco-label, products must comply with environmental and social requirements. Just like the Nordic Ecolabel, these criteria are not identical across the 61 products and service groups currently covered.

EU Ecolabel is the eco-label scheme set up by the European Commission. It was established in 1992 and now includes 35 categories for more than 10,000 products. As the only label recognised throughout Europe, it encourages businesses to market products and services that cause less impacts on the environment.

Examples of requirements for bio-based products

Using the Blue Angel Ecolabel as an example, this section looks at how wood products are covered in Type I eco-labelling. In Blue Angel (2013), wood products are divided into three categories:

- Composite wood panels that include fibreboards, wood-core plywood, chipboards and veneer plywood boards.
- Wood products, products such as furniture or slated frames.
- Floor coverings, panels and doors.

Table 9.1 illustrates the requirements for wood floor covering products in the Blue Angel Ecolabel. These requirements are prescribed in several sections, which cover the different life cycle stages of a product and the communication of the label. Most of the requirements are compulsory, meaning they must be met and verified by a third party before the label is awarded.

Wood floor coverings are considered in a number of Type I eco-labels. While all labels have their particular focus [e.g. the EU Ecolabel scheme is the only one to refer to genetically modified wood and prohibit it (European Commission, 2010)], some of the requirements are common to most labels (e.g. the origin of wood, provenance from sustainably managed forest). However, whilst some of the requirements appear very similar, there may be variations in the calculation methods or performance levels. For instance, for the energy consumption requirements, the calculation method is different between the Nordic Swan and EU Ecolabel, as well as the limit value set by the respective documents. The results of the assessment are therefore not comparable, and a product that passes the requirements of one label may not meet the requirements of another.

Table 9.1 Requirements for wood floor coverings in Blue Angel Ecolabel (2013)

Section	Requirement	Level
Manufacture	Understand the origin of the wood • 100% from legal sources • >50% by weight from sustainable forest	Compulsory
	Do not exceed the limit value for formaldehyde in wood-based materials	Compulsory
	Prohibit the use of carcinogenic, mutagenic and reprotoxic (*CMR*) substances	Compulsory
	Do not exceed the limit value of VOC emissions from the coating systems	Compulsory
Use	Do not exceed the limit values of emissions for indoor air quality	Compulsory
	Carry out an odour test	Optional
	Ensure that packaging is designed to allow the outgassing of volatile components	Compulsory
	Be sure that product meets serviceability requirements	Compulsory
Recycling and disposal	Prohibit the use of halogenated organic compounds in the manufacture of the product	Compulsory
	Only use the flame retardants listed	Compulsory
	Prohibit the use of biocides	Compulsory
Declaration and consumer information	Be sure to include the listed information (e.g. name and instruction recommendations) in the product declaration	Compulsory
Advertising messages	Prohibit terms listed in advertising messages	Compulsory
	Prohibit terms listed, such as 'organic' or 'eco' to describe product attributes	Compulsory

9.3.1.3 Type II—Self-declared environmental claims

Type II environmental labels are not considered in any more detail here as they are highly variable and defined as 'self-declared' environmental claims made by manufacturers and businesses.

9.3.1.4 Type III—Environmental declarations based on LCA

An EPD is a declaration based on third-party verified LCA. The LCA and the verification and issue of a construction product EPD are carried out in accordance with applicable international standards that set out the framework, principles, requirements and rules (ISO 14025 (ISO, 2006a); ISO 14040, (ISO, 2006b); ISO 14044 (ISO, 2006c); ISO 21930 (ISO, 2007)). The LCA result presented in an EPD is a table of values in different units of measurement that represent different environmental impact indicators. There is no pass or fail criteria, so having an EPD is not necessarily a representation or mark of 'good' or 'bad' environmental performance but simply a measure of

performance. A number of EPD programmes or schemes for construction products have been developed across the world in accordance with the relevant standards mentioned.

The broad nature of these standards allowed interpretations, which meant that varying results were generated based on the same standards for the same product from different practitioner sources. Such differences potentially extended to the environmental indicators reported, and different environmental indicators could be used by different schemes. So, in 2004, in order to harmonise the development of EPD in Europe, the European Committee for Standardisation (CEN) set up Technical Committee 350 (CEN/TC 350, CEN, 2012a). The committee focused on three aspects (environmental, social and economic) and developed standards for the assessment of construction products (the product level) and for whole buildings (the building level). From the committee work, a European standard for construction products EPD was published (EN 15804, CEN, 2012b). EN 15804 (CEN (2012b)) is much more prescriptive than ISO 21930 (ISO (2007)), defining the approach to follow, the indicators to be declared and which stages of a product life cycle and processes need to be included. Table 9.2 provides the list of impact indicators that need to be included in an EN 15804 (CEN (2012b)) EPD.

There are three main types of EPD: cradle-to-gate, cradle-to-gate with options and cradle-to-grave, shown in Fig. 9.4, adapted from CEN (2012b). This modular approach allows the optional selection of different life cycle stages (known as information modules) relevant to the owner of the declaration, the intended user of the declaration or the user of the product concerned.

For wood and wood-based products, an additional standard has been developed by the Technical Committee CEN/TC 175 rand sawn timber. This standard, EN 16485 (CEN (2014b)), complements the rules defined in EN 15804 (CEN (2012b)) and is therefore used in conjunction with EN 15804 (CEN (2012b)). Using EN 16485 (CEN (2014b)), aspects relevant to the specific product category (wood) are considered, such as the renewability of wood and its potential carbon neutrality, carbon storage, energy and water content of wood. Further, in order to harmonise the quantification of the potential benefits associated with carbon storage in wood and wood-based products, an LCA calculation method (EN 16449, CEN, 2014a) has also been published.

9.3.1.5 How to obtain an EPD in Europe

EPD are verified and issued by EPD schemes or programme operators (*PO*). There are several PO in Europe, typically one in each country or region. Examples of established PO include BRE (the United Kingdom), IBU (Germany) and AFNOR (France). EPD programmes are membership based, so the first step in obtaining an EPD is identifying and joining an appropriate programme (Construction Products Association, 2012).

The LCA for deriving the data for the EPD needs to be carried out by an LCA practitioner using appropriate PCR. The programme will either develop a PCR or select an existing PCR (which is an interpretation of EN 15804, CEN (2012b)), developed in accordance with ISO 14025 (ISO (2006a)) by an expert group including manufacturers and other stakeholders and is peer reviewed, and the entire development process is moderated by a PO. A valid PCR should be publicly available and published on the

Table 9.2 EN 15804 (CEN (2012b)) environmental impact indicators

	Indicator	Unit
Impact assessment	Global warming potential, GWP	kg CO_2 equiv
	Depletion potential of the stratospheric ozone layer, *ODP*	kg CFC 11 equiv
	Acidification potential of land and water, *AP*	kg SO_2 equiv
	Eutrophication potential, *EP*	kg $(PO_4)_2$ equiv
	Formation potential of tropospheric ozone photochemical oxidants, *POCP*	kg Ethene equiv
	Abiotic resource depletion potential for elements, *ADP* elements	kg Sb equiv
	Abiotic resource depletion potential for fossil fuels, ADP fossil fuels	MJ, net calorific value
Resource use	Use of renewable primary energy excluding energy resources used as raw material	MJ, net calorific value
	Use of renewable primary energy resources used as raw material	MJ, net calorific value
	Use of nonrenewable primary energy excluding primary energy resources used as raw material	MJ, net calorific value
	Use of nonrenewable primary energy resources used as raw material	MJ, net calorific value
	Use of secondary material	kg
	Use of renewable secondary fuels	MJ
	Use of nonrenewable secondary fuels	MJ
	Net use of fresh water	m^3
Waste	Hazardous waste disposed	kg
	Nonhazardous waste disposed	kg
	Radioactive waste disposed	kg
Output flows	Components for reuse	kg
	Materials for recycling	kg
	Materials for energy recovery (not being waste incineration)	kg
	Exported energy	MJ for each energy carrier

PO's website. Some PO, such as IBU, have specific PCR for specific product groups, and others, such as BRE, have one PCR covering all construction products.

The LCA study can be done either in-house (if the appropriate expertise is available) or externally using a consultant. The study is carried out using appropriate software or tools—the PO can provide guidance on the best approach to take. Some POs have launched online LCA tools to provide access to data and a route to EPD for a much wider audience than has been possible before, for example, BRE LINA www.bre.co.uk/lina

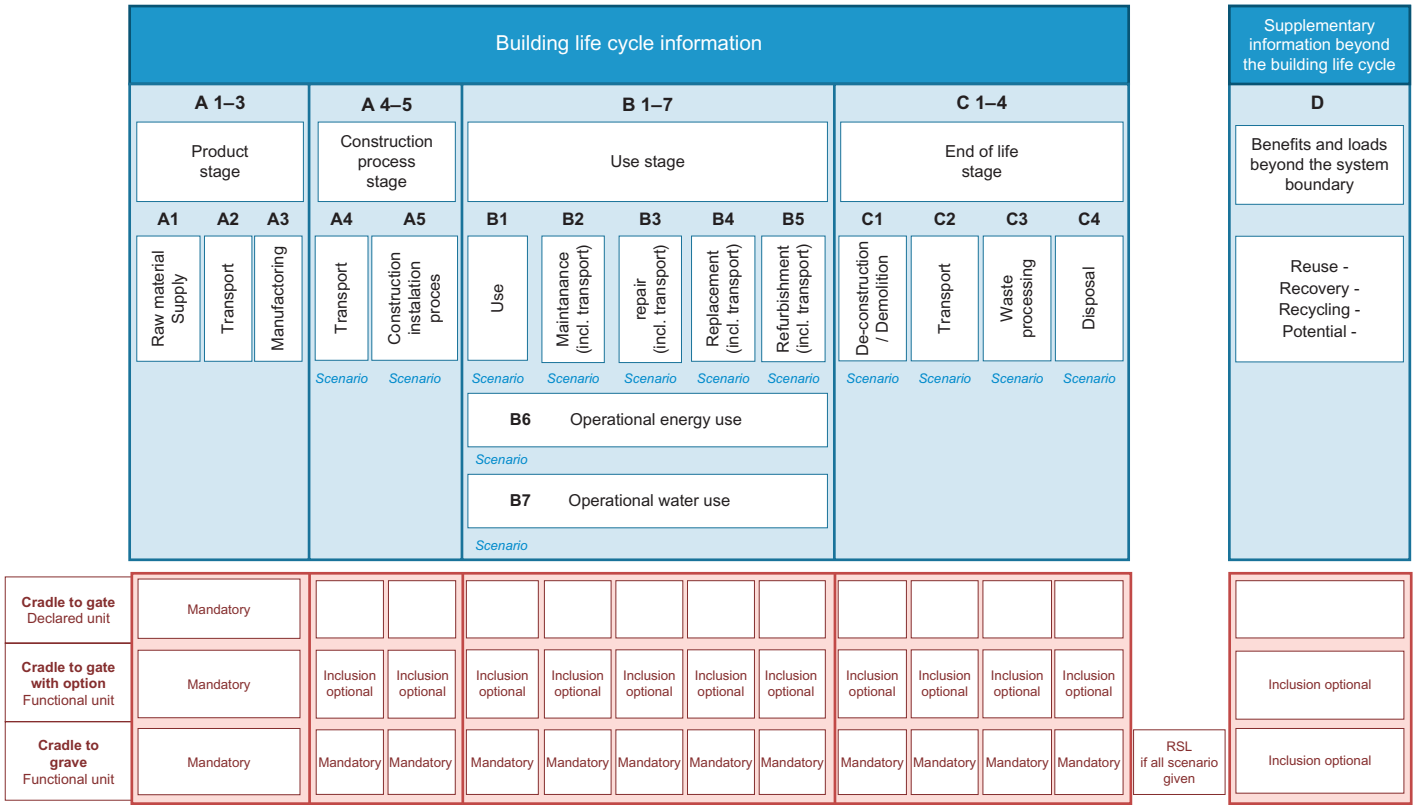


Fig. 9.4 Boundaries of the study for cradle-to-gate, cradle-to-gate with options or cradle-to-grave.

The completed LCA study results are then verified by a qualified verifier external to the study (this is the 'third-party' verification) usually appointed by the programme. The verification process checks the information presented in the EPD and the study as documented in an LCA report for issues including compliance with standards, plausibility and compliance with the programme rules. The verifier determines if the EPD is suitable or not for issue by the programme, and the PO puts in place measures for final approval and the resolution of disputes. The entire process of independent verification assures that the EPD is robust and it is a transparent declaration that is fit for purpose. Following successful verification, the EPD is issued by the programme and published on a public listing service provided by the PO (typically, the PO's website, e.g. BRE EPD, is published on the GreenBookLive website www.greenbooklive.com). EPD are valid for 5 years, as dictated by EN 15804 (CEN (2012b)), and it is the responsibility of the PO to ensure its website is up-to-date, whilst the owner of the EPD ensures that the published EPD is representative of the actual product throughout the validity of the EPD.

In terms of content of the EPD, EN 15804 (CEN (2012b)) defines what information must be included in an EPD, but the overall look is at the discretion of the PO and, to some extent, the owner of the EPD. Examples of existing EPD of wood products are provided in Fig. 9.5.

9.3.1.6 Examples of certifications

Table 9.3 provides a summary of EPD programmes in Europe. Most of these schemes have been operating for many years, and their schemes have evolved as the standards have changed. All offer EN 15804 (CEN (2012b)) EPD.

Although EN 15804 (CEN (2012b)) provides a more harmonised approach to developing EPD for construction products, it does not yet provide full recognition amongst the scheme operators. In 2011, the EPD programmes from Sweden, Spain, Portugal, Poland, Norway, the Netherlands, Italy, Great Britain, Germany, France and Finland therefore established an international nonprofit association known as the ECO Platform. It is a group of PO, LCA practitioners, industrial associations and other stakeholders with a primary objective of developing a common European framework for EPD based on ISO 14025 (ISO (2006a)) and EN 15804 (CEN (2012b)). The ECO Platform EPD should be applicable across Europe. Covering over 80 product categories, more than 350 products have been certified since 2012.

9.3.1.7 Drivers

This section explores the drivers that make businesses choose to obtain voluntary environmental labels—EPD in particular—for their products. The main drivers identified are building-level assessment, Conformité Européenne (*CE*) marking and country-specific approaches.

Whole building assessment methods

There are several building-level assessment methods used in Europe. The most popular ones are *BREEAM* (Building Research Establishment Environmental Assessment Methodology), *LEED* (Leadership in Energy and Environmental Design), *HQE* (Haute Qualité Environnementale) and *DGNB* (Deutsche Gesellschaft für Nachhaltiges Bauen). These are described in more detail in Section 9.3.2 including how they promote the use of EPD.

Fig. 9.5 Examples of environmental product declarations (EPD) for wood products including a Medite MDF product and a Protec treated timber landscaping product.

(Continued)

Fig. 9.5, Continued

CE Marking

From 1 Jul. 2013, according to the Construction Products Regulation (*CPR*), it has become mandatory for all construction product manufacturers in Europe to draw up a declaration of performance and apply CE marking. This applies to any construction products that are covered by a harmonised European standard (*hEN*) or conform to a European Technical Assessment, which has been issued for it, when the product is placed on the market. This is a significant change as a CE mark under the provisions of the existing Construction Products Directive (*CPD*) was previously voluntary in most European countries.

The harmonised technical specification for a product defines European Economic Area (*EEA*)-wide methods of assessing and declaring all the performance characteris-

Table 9.3 Environmental product declaration programmes in Europe

	The United Kingdom	Germany	Sweden	France	Norway
Scheme	BRE EN 15804 EPD	IBU	EPD Environdec	INIES (database)—FDES	EPD Norge
Logo					
Date of creation	1999	2006	2007	2004	2002
Number of categories	All construction products	41	13	–	19
Number of EN EPD	>100	>160	>30	>130	>50
Number of products		1456	567	>1600	327

tics required by regulations in any member state, which affect the ability of construction products to meet seven basic requirements for construction works (*BRCW*):

(1) mechanical resistance and stability
(2) safety in case of fire
(3) hygiene, health and environment
(4) safety and accessibility in use
(5) protection against noise
(6) energy economy and heat retention
(7) sustainable use of natural resources

To complete the seventh requirement, the construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable. Stakeholders must also ensure that the construction works, their materials and parts can be reused or recycled after demolition. Whilst BRCW (7) focuses on recycling and the use of LCA, it is not mandatory to have an EPD to fulfil the BRCW (7). However, the CPR has created a system of assessment and verification of constancy of performance, which defines the degree of involvement of the third parties in the process of certification. For a CE mark certification, the degree of involvement must be the highest one (system 1+). It means that the certification shall be carried out by a third party and continuously surveyed and subjected to an audit test. Therefore, because EPDs are third-party verified, requirement related to environmental performance can be fulfilled by EPDs.

Specific country drivers

While EPD is still voluntary, some countries have decided to promote products that cause less impacts on the environment by setting legislation. These legislations do not

specifically require EPD, but EPD can support a manufacturer in meeting the requirements. A few examples of country-specific legislations are provided in this section.

i. Belgium

Since 2015, when a manufacturer wants to declare environmental credentials for his product, they shall first carry out an LCA and register the product into the database www.environmentalproductdeclarations.eu, which is a publicly accessible website (SPF Santé Publique, 2015). Moreover, each declaration based on LCA shall be verified by a third party. Because EPDs meet the requirements, they can be used for these environmental declarations.

ii. France

The Department of Housing and Urban Planning (*DHUP*) has published a decree (DHUP, 2013) concerning building materials. This decree affects every organisation that wants to put a construction product on the French market and declare their environmental credentials. Therefore, they shall make a complete list of impacts on the environment of the product with a life cycle approach and have a third-party control the quality of these environmental declarations. Thus, Fiches de déclaration environnementale et sanitaire (*FDES*) (EPD) are promoted by this regulation.

The aim of this section was to define environmental labels and to identify the different types: Type I (eco-labels), Type II (self-declarations) and Type III (EPD). Some of the labels are pass/fail (Type I), and others are nutritional (Type III). Both Type I and Type III are third-party verified and can be used to communicate from business to business. While the results from one label to another cannot be compared, much work has been done for the harmonisation and recognition of EPD across Europe, with the introduction of standards such as EN 15804 (CEN (2012b)). Environmental labels are largely voluntary, but drivers such as building-level assessment schemes are rewarding the use of EPD, and as the demand for such scheme increases, the demand for EPD will also increase.

9.3.2 Environmental assessment of buildings

The building sector can contribute significantly towards necessary emission reductions with appropriate construction of new sustainable buildings and retrofitting of existing buildings. One strategy for achieving that transformation is most widely known by the term green building. Green building can be characterised as integrated building practices that aim to significantly reduce the environmental footprint of a building in comparison with standard practices. Descriptions of green building generally focus on a number of common elements, especially siting, energy, water, materials, waste and health. One of the most salient features of green building is the integration of many aspects of sustainable building. Although individual elements can be addressed separately, the green building approach is more comprehensive, focusing on the environmental footprint of a building over its life cycle, from initial design and construction to operations during the building's useful life and through end-of-life strategies. The desire to integrate the various elements of green building has led to the development of rating and certification systems for assessing how well a building project meets a specified set of sustainability criteria. Attributes of sustainable buildings with relation

to the triple bottom line consist of three categories: environmental, social and economic (Gorse *et al.*, 2016). The environmental attributes include energy and natural resources, water conservation, material use, durability and waste, land use, transport and accessibility and pollution. The social attributes include usability and function, indoor environment conditions (health and wellbeing and architectural consideration), cultural and aesthetic and innovation and design. And the economic attributes include flexibility and adaptability, economic performance and affordability, building manageability and whole life function and value.

9.3.2.1 Whole building assessment schemes

One of the main drivers for manufacturers to create an EPD for their bio-based construction product is that they are rewarded in whole building assessment schemes. Whole building assessment methodologies provide rating schemes that consider the above sustainability attributes in their assessment categories. There are many green building rating systems such as the BREEAM from the United Kingdom, DGNB from Germany, HQE (France) and Green Star (Australia). In the United States, the most popular system is the LEED. In Japan, the Comprehensive Assessment System for Built Environment Efficiency (*CASBEE*) was developed. While each system has unique features, significant overlaps exist amongst them. Sinha and Knowles (2014) compared the assessment categories of four major international green building rating systems: LEED, Green Star, DGNB and CASBEE. The authors concluded that these systems have significant commonalities in their various assessment categories and that the differences are largely in the use and definition of terminology. However, it is important to consider the region-specific developments of the rating systems, which contributes variability to the many rating systems.

BREEAM—United Kingdom

Developed by BRE in 1990, the BREEAM was the first building-level assessment method. Today, more than 560,000 buildings have been certified in more than 75 countries, and over 2,200,000 are in the process of being assessed. Two-thirds of the buildings certified in Europe are certified to BREEAM, so more focus has been given here to this building-level assessment method. BREEAM awards a rating (pass, good, very good, excellent and outstanding), which is an overall reflection of the environmental impact of the building. While the scheme has a strong focus on environmental issues, it also covers social and economic aspects of the building. BREEAM covers several issues, such as transport, energy, materials, health and wellbeing, water, management, wastes, ecology and pollution. Depending on the building type, the building life cycle stage and whether it is in the United Kingdom or not, the number of credits awarded for each category and the weighting applied vary. In BREEAM UK New Construction, for example, a weighting of 13%–17% is applied to the materials section, which is quite

significant. A number of issues are covered in the materials section: mainly responsible sourcing and environmental impact assessment of materials. More than 50% of the credits are awarded for looking at the environmental impact of materials. BREEAM recognises that the importance of the impact of materials will increase as buildings become more energy-efficient (material consumption and energy use during the operation of the building make up most of the carbon footprint of the building). BREEAM published their strategy for evaluating materials in 2015, and it states that they will continue to reward the use of products with EPD but will also reward a whole building-level assessment approach (in line with EN 15978 (CEN, 2011)).

BREEAM sets the standard for best practice in sustainable building design, construction and operation and has become one of the most comprehensive and widely recognised measures of a building's environmental performance internationally. It encourages designers, clients and others to think about low-carbon and low-impact design, minimising the energy demands created by a building before considering energy efficiency and low-carbon technologies. A BREEAM assessment uses recognised measures of performance in a broad range of categories and criteria from energy to ecology. They include aspects related to energy and water use, the internal environment (health and wellbeing), pollution, transport, materials, waste, ecology and management processes.

LEED—United States

In 2000, the US Green Building Council (USGBC) launched the LEED certification scheme. The scheme is now present across more than 150 countries, and currently more than 45,000 projects have been certified. The LEED certification process awards building with a medal (bronze, silver, gold or platinum) reflecting environmental impact and outcomes on local communities. LEED covers similar categories to those listed in BREEAM. Since the latest version, LEED v4, the category 'Building Product Disclosure and Optimisation' encourages the use of products with EPD.

DGNB—Germany

The German Sustainable Building Council (DGNB) scheme was founded in 2007. It is a relatively new scheme, but already more than 1000 projects have been certified or precertified. The scheme awards certified buildings with a gold, silver or bronze medal, which indicates the environmental, economic and social credentials of the building. DGNB categories are similar to those covered in BREEAM, and DGNB encourages the assessment of the materials through the use of a whole building LCA approach. The impact of materials accounts for 14% of the overall DGNB score. The methodology described is broadly in line with EN 15804.

DGNB is a 'second-generation' rating system, giving a more holistic evaluation of the entire life cycle of a building, and adapted schemes are being developed in several countries worldwide. Compared with BREEAM and LEED, DGNB provides more coverage of social and economic attributes. In its scoring system, weights can vary from zero to three (Bedeutungs and Anpassungsfaktor) depending on the system's societal or political relevance and its importance for a specific use profile. Also, an important feature in DGNB is the explicit inclusion of the economy, so that lifecycle costs and stability in value are accounted for in the certificate.

HQE—France

The NF HQE Certification was first established in 2004 by the HQE Association and AFNOR Certification. The scheme considers 14 environmental targets, organised in 4 issues (eco-construction, eco-management, comfort and health) and the scores are passable, bien, très bien, excellent and exceptionnel. HQE rewards the use of EPD, but only those produced by Environmental and health reference data for building (INIES), which are Fiches de déclaration environnementale et sanitaire (FDES). Moreover, since 2011, the HQE Association has both the role of owner and manager of the INIES database and promotes even more FDES.

9.3.2.2 *Sustainability assessment of buildings using EN 15978 (CEN (2011))*

The previous section looked at the environmental assessment of products and mentioned the work carried out by CEN/TC 350 in developing standardised methods for the assessment of the sustainability aspects of new and existing construction works (buildings and civil engineering). This committee has developed standards not only at product level (covering environmental, social and economic issues) but also at building level. In 2012, CEN/TC 350 published a new European Standard for the sustainability assessment of buildings EN 15978 (CEN (2011)). This standard provides guidance to the calculation method, based on LCA (which shall also be ISO 14040 (ISO (2006b)) series compliant), to assess the environmental credentials of buildings. EN 15978 (CEN (2011)) gives the following:

- The description of the object of assessment.
- The system boundary that applies at the building level.
- The procedure to be used for the inventory analysis.
- The list of procedures for the calculations of these indicators.
- The requirements for the data necessary for the calculation.

It takes a similar approach to EN 15804 (CEN (2012b)) in covering all the stages of the building life cycle, and the list of indicators is the same. EN 15978 (CEN (2011)) is based on the data obtained from EPD. EN 15978 (CEN (2011)) also provides the requirements and means to report and communicate the outcomes of the assessment.

The publication of EN 15978 (CEN (2011)) prescribes an LCA approach for the environmental assessment of buildings. However, the approach is one followed mainly by LCA experts as it requires considerable technical knowledge. So, it is important that such a standard is integrated into tools already used by architects and designers to ensure a wider uptake of such an approach at early stages of the building design. Software providers have been working on the development of their existing tools to enhance them with the capabilities to integrate EN 15978 (CEN (2011)) principles. Some of the tools that provide the capability to carry out whole building LCA are now presented briefly.

IMPACT compliant tools

IMPACT is a methodology and database that can be implemented into tools to make them IMPACT compliant. The methodology and database were launched in 2011 and are the results of a three-year research project conducted by BRE, AEC3, IES Ltd and WD Rethinking. The IMPACT methodology is in line with EN 15978 (CEN (2011)) and allows the integration of LCA data in building information modelling (BIM) type tools. At the time of writing, there are two IMPACT compliant tools: IES-VE and eTool. These tools allow users to calculate the embodied impact of a building and to analyse and improve the building design. The use of IMPACT compliant tools is rewarded in BREEAM.

Tally

Tally is an application that fully integrated itself in Autodesk Revit software. In 2008, KT Innovations in partnership with Autodesk Sustainability Solutions and Thinkstep began developing Tally as an add-on to Revit, making it is an easy-to-use application for Revit users. By defining relationships between Revit elements and the Tally LCA database, Tally allows the user to quantify the environmental impact of building materials using a building life cycle approach and to compare different design options. Tally is now approved for LEED v4 to achieve Building LCA.

ELODIE

ELODIE is the French web-software assessing environmental credentials of buildings. It was created in 2006 by the Centre Scientifique et Technique du Bâtiment (CSTB) and the Direction générale de l'urbanisme, de l'habitat et de la construction (DGUHC) and released in the late 2008. ELODIE software provides a solution to the INIES database issues as the FDES were not being used by the construction designers because they were difficult to understand. Because ELODIE is linked with INIES, users can choose a product within the database to model their building. After selecting all the products, ELODIE uses the information contained within the FDES to provide an overall environmental impact of the building. This impact was calculated using the NF (2004) standard, but this has now been withdrawn (August 2016) and, by reference to EN 15978 (CEN (2011)), now EN 15804 (CEN (2012b)), is required. It is compliant with not only HQE that is the French scheme to assess performance of building but also BREEAM.

Bionova Ltd

One of the construction LCA software leaders has brought an innovative solution to make LCA ‘in a single click’. The solution, One Click LCA, is a cloud-based

software that uses information from BIM software (Autodesk Revit, ArchiCAD and Tekla Structures, as long as it uses IFC format) to quickly and easily calculate LCA of buildings. It is linked with the Bionova database that contains verified EPD, publicly available database and allows users to add specific EPD. The software is third-party verified for compliancy with EN 15978 (CEN (2011)), ISO 21931-1 (ISO (2010)), ISO 14040 (ISO (2006b)) and EN 15804 (CEN (2012b)). Furthermore, the software has been officially approved to provide LCA for more than 20 certification schemes (amongst them are LEED v4, BREEAM International, DGNB and HQE).

The construction sector plays a key role in the consumption of energy and resources and in solid waste accumulation; it is important to quantify the environmental performance of buildings to communicate their potential environmental impacts and aspects and their influence on sustainable development.

A building uses most of its energy during its service life, which is dominated by operational energy demands to cool, heat and light the building. This use phase of a building is often said to contribute 70%–90% of its environmental impact (Beccali *et al.*, 2013; Cuéllar-Franca and Azapagic, 2012; Ortiz *et al.*, 2010; Citherlet and Defaux, 2007; Newsham *et al.*, 2009). Therefore, the adoption of a life cycle approach, where not only current energy concerns are accounted for but also long-term energy, environmental and social impacts should be adopted and integrated into design. Parallel to the development of sustainable buildings, the environmental impact of materials, products and new production processes throughout the life cycle of buildings with an analysis of LCA and life cycle cost analysis must be assessed. Additionally, materials that are not harmful to human health and that are recyclable are priorities for selection, which is in part within an LCA approach. Certification schemes such as C2C have material health as a primary material quality. Furthermore, for each developed product, the scenario at the end of its first life cycle should be determined and has a critical significance in the overall product LCA outcome. In the last few decades, thousands of studies with the aim to reduce the environmental impact of buildings have been performed, and it continues to be a very active development sector. At the same time, refined approaches for assessing a building's sustainability are under development (Haapio and Viitaniemi, 2008; Ding, 2008; Sinha and Kutnar, 2012).

Newly published standards for sustainability for construction works (CEN TC350) open opportunities for EU-wide harmonisation of calculations and reporting of a building's environmental impacts. The most important standards are EN 15804 for construction product EPDs and EN 15978 for assessment of environmental performance of new and existing construction works. In Mar. 2011, the CPR (305/2011) 2011 was introduced, replacing the CPD (89/106/EEC) 1993. The CPR came into full force in Jul. 2013. In order to develop a framework that allows for comparability of environmental performance between products, ISO 14025 (ISO (2006a)) was introduced. This describes the procedures required to produce Type III EPD. This is based on the principle of developing PCR, which specify how the information from an LCA is to be used to produce the EPD. For the construction sector, the core PCR is EN 15804 (CEN (2012b)). Currently, there are 28 EPD programmes referring to ISO 14025 (ISO (2006a)) that together provide 2256 PCR documents and more than 3600 EPDs (Passer *et al.*, 2015). Passer *et al.* (2015) performed a comprehensive comparison of national EPD

programmes (Austria, Belgium, France, Germany and Switzerland) that are all based on EN 15804 (CEN (2012b)). The study concluded that the EPD programmes of listed countries are very similar and that harmonisation could only be reached by development of general guidelines and mutual recognition amongst different schemes. On the other hand, Lasvaux *et al.* (2015) compared two LCA databases, the Ecoinvent generic database and the EPD database developed in France. The databases were compared on three building LCA case studies: brick, reinforced concrete and timber frame structures. It was found that both databases can present very different values depending on the type of environmental indicator. For example, global warming potential has approximately 25% deviation amongst the databases, whilst photochemical ozone formation can vary amongst EPD and generic database with 100% or more. This indicates a lack of consistent metrics and guidance for practitioners, which presents a barrier to the widespread use of LCA in the European construction sector. In the European project EeBGuide, an online InfoHub was developed with the aim to provide guidance for LCA studies for energy-efficient buildings and present an interactive platform between research activities, standardisation activities and the practical implementation of LCA in the construction sector (Lasvaux *et al.*, 2014a). The platform is unfortunately not maintained, which is needed to assure widespread use of the InfoHub for LCA of construction works.

As sustainability becomes a dominant aspect of building development, the environmental impact of building materials should be included during planning with special attention paid to the life cycle and embodied energy of the materials used. Therefore, the LCA methodology should be used to reveal the environmental and energy performances of the used materials and the developed products through the whole life cycle. Since the 1980s, when the first LCA methodology was developed, till today, numerous methodologies to classify, characterise and normalise environmental effects have been developed. The most common, for example, CML 2 (2000), IPCC GHG emissions, Ecopoints 97 and Eco-indicator 99 (PRé Consultants, 2010), are focused on the following impact categories: acidification, eutrophication, ozone layer depletion, various types of ecotoxicity, photochemical ozone formation, resource depletion and global warming. As solutions are sought to reduce the impacts of buildings, LCA provides an objective measure for comparing building designs.

Building performance assessment can be very complex, as it must respond to multiple criteria, like energy consumption, acoustical performance, thermal occupant comfort, indoor air quality and many other issues. The functional unit has to be carefully defined. An assessment requires the use of predictive models that involve numerous design and physical parameters as their inputs (Hopfe *et al.*, 2013). Since these input parameters and the models that operate on them are not precisely known, it is imprudent to assume deterministic values for them. A more realistic approach is to introduce ranges of uncertainty in the parameters themselves or in their derivation, from underlying approximations.

Lasvaux *et al.* (2014b) delivered a list of future research needs in the field. They emphasised the development of dynamic LCA (taking into account spatial and temporal variations) for assessing the use phase of the building. It is suggested that parameters such as the degradation of performances of construction products and technical

equipment and the precision of environmental data for energy processes for the electricity mix should be investigated. A further temporal dimension relates to the inherent uncertainties of end-of-life practices occurring in at least 50–100 years, for the buildings built today. In the absence of alternatives, current practices are most often assumed. Also, Passer *et al.* (2012) discussed the need for integrated LCAs that include the technical building equipment in evaluations of environmental performance of buildings. Hollberg and Ruth (2016) developed parametric model to try and address the need for design-integrated LCA and wider use of LCA in the building design process. The parametric model parameterises all input, including geometry, materials and boundary conditions, and generates LCA in real time. The simplified LCA can be used by architects to design solutions with minimum environmental impacts of new building or when designing the retrofitting of a single-family house.

Kuittinen *et al.* (2013) calculated the energy efficiency and carbon efficiency for eight wood-framed buildings from different European regions (Austria, Finland, Germany, Italy and Sweden). Using real buildings as an example, the study showed how the use of wood affects the carbon footprint and primary energy demand of buildings and concluded that country-specific data should be used in calculations.

Carre (2011) performed a cradle-to-grave LCA to compare environmental indicators of five different constructions of a typical single-storey Australian home with the same energy performance. Building materials, construction, operation, maintenance and end-of-life management phases were included. The results showed that global warming, photochemical oxidation formation, eutrophication, resource use and embodied energy are remarkably similar between the construction types. Land use, water use and solid waste indicators show more pronounced differences between construction types, with water and land use tending to be higher for timber-based construction types and solid waste tending to be higher in concrete slab designs. Variation between construction types is minimal for most indicators due to the dominance of the operational aspect of the building life cycle, which contributes 55%–86% of global warming impacts. Indicators such as land use, water use and solid waste are less affected by operation so it tends to be driven more by construction and end-of-life processes. Furthermore, a comparison of life cycle impacts excluding operation showed that timber-based construction tends to have lower global warming impacts than alternatives. In general, construction types incorporating timber tend to have lower global warming, resource use and embodied energy outcomes.

Robertson *et al.* (2012) quantified and compared the environmental impacts associated with alternative designs for a typical North American mid-rise office building. Two scenarios were considered: a traditional cast-in-place, reinforced concrete frame and a laminated timber hybrid design, which utilised engineered wood products (CLT and glulam). The results indicated that the laminated timber building design offered a lower environmental impact in 10 of 11 assessment categories.

The optimal design of buildings typically must account for multiple and competing objectives by simultaneously minimising energy consumption and environmental impact, without significantly increasing financial costs. Although meeting individual objectives by applying tailored strategies may be relatively simple, achieving the very high levels of performance is required to reduce energy use to nearly zero,

whilst maintaining minimal costs is significantly more complex. This goal ideally requires applying the optimal combination of several strategies, which may be obtained through building energy simulations. However, simultaneously optimising a comprehensive set of passive solar design strategies quickly leads to design spaces that may be prohibitively large for available computational resources. Stevanović (2013) gave exhaustive review of the studies about simulation-based optimisation of passive solar design strategies. Although it is relatively simple to reduce the energy use up to some extent by applying individual strategies, very high levels of energy performance ideally require application of the optimal combination of several strategies, verified through building energy simulations, which are expected to be developed in the future. Furthermore, the service life information of a building plays an important role in life cycle studies, and therefore, not only technical factors influencing the lifetime of a building but also consumer behaviour should be considered. Aktas and Bilec (2012) studied the US residential building lifetime and its impact on LCA results. The study concluded that a product's actual lifetime was usually different than what the product was designed for and was determined by consumer behaviour.

Bio-based materials and construction products have a tremendous opportunity as we continue as society to strive for lower-impact buildings and construction works. The significance of the construction product sector on climate change through attributed emissions of carbon dioxide and other GHGs associated with material extraction, processing and product manufacture warrants a keen focus on lower environmental impact products. With the stored carbon in bio-based materials, we have a firm foundation to develop low-impact products for the future. Products that meet the need of users meet service life expectations and deliver wider benefits such as health and wellbeing to building occupants.

References

Aktas, C.B., Bilec, M.M., 2012. Impact of lifetime on US residential building LCA results. Int. J. Life Cycle Assess. 17 (3), 337–349.

Allison, C., Carter, A., 2000. Study on Different Types of Environmental Labelling (ISO Type II and III Labels). Final Report for DG Environment. European Commission, Brussels, Belgium.

Ardente, F., Beccali, M., Cellura, M., Mistretta, M., 2008. Building energy performance: a LCA case study of kenaf-fibres insulation board. Energ. Buildings 40, 1–10.

Arena, U., Mastellone, M.L., Perugini, F., Clift, R., 2004. Environmental assessment of paper waste management options by means of LCA methodology. Ind. Eng. Chem. Res. 43, 5702–5714.

Beccali, M., Cellura, M., Fontana, M., Longo, S., Mistretta, M., 2013. Energy retrofit of a single-family house: life cycle net energy saving and environmental benefits. Renew. Sustain. Energy Rev. 27, 283–293.

Berndes, G., Ahlgren, S., Borjesson, P., Cowie, A., 2013. Bioenergy and land use change state of the art. WIREs Energy Environ. 2013 (2), 282–303.

Biswas, W., Graham, J., Kelly, K., John, M.B., 2010. Global warming contributions from wheat, sheep meat and wool production in Victoria, Australia—a life cycle assessment. J. Clean. Prod. 18, 1386–1392.

Blom, I., Itard, L., Meijer, A., 2010. Environmental impact of dwellings in use: maintenance of façade components. Build. Environ. 45, 2526–2538.

Blue Angel, 2013. Basic Criteria for Award of the Environmental Label, Low-Emission Floor Coverings. Panels and Doors for Interiors Made of Wood and Wood-Based Materials. Umweltbundesamt (Federal Environment Agency), Dessau-Roßlau, Germany. www.blauer-engel.de/en.

Börjesson, P., Gustavsson, L., 2000. Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. Energy Policy 28, 575–588.

Boulding, K.E., 1966. The economics of the coming spaceship earth. In: Jarrett, H. (Ed.), Environmental Quality in a Growing Economy: Essays From the Sixth RFF Forum. John Hopkins University Press, Baltimore, MD, pp. 3–14.

Brandão, M., Levasseur, A., Kirchbaum, M., Weidema, B., Cowie, A., Jorgensen, S., Hauschild, M., Pennington, D., Chomkhamsri, K., 2013. Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. Int. J. Life Cycle Assess. 18, 230–240.

Brander, M., 2015. Response to "Attributional life cycle assessment: is a land-use baseline necessary?"—appreciation, renouncement, and further discussion. Int. J. Life Cycle Assess. 20, 1607–1611.

Bribián, I.Z., Usón, A.A., Scarpellini, S., 2009. Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Build. Environ. 44, 2510–2520.

Bribián, I.Z., Capilla, A.V., Usón, A.A., 2011. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. 46, 1133–1140.

BSI, 2008. PAS2050 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services. British Standards Institute, London, UK.

Buchanan, A., Levine, S., 1999. Wood-based building materials and atmospheric carbon emissions. Environ. Sci. Pol. 2, 427–437.

Cacho, O., Hean, R., Wise, R., 2003. Carbon-accounting methods and reforestation incentives. Aust. J. Agric. Resour. Econ. 47, 153–179.

Carre, A., 2011. A comparative life cycle assessment of alternative constructions of a typical Australian house design. Project report PNA147-0809. Forest and Wood Products Australia, Melbourne.

CEN, 2011. EN 15978:2011. Sustainability of construction works—assessment of environmental performance of buildings—calculation method. European Committee for Standardization, Brussels, Belgium.

CEN, 2012a. CEN/TC 350:2012. Sustainability of construction works. European Committee for Standardization, Brussels, Belgium.

CEN, 2012b. EN 15804:2012. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products; German version EN 15804:2012+A1, 2013. European Committee for Standardization, Brussels, Belgium.

CEN, 2014a. EN 16449:2014. Wood and wood-based products—calculation of the biogenic carbon content of wood and conversion to carbon dioxide. European Committee for Standardization, Brussels, Belgium.

CEN, 2014b. EN 16485:2014. Round and sawn timber. Environmental product declarations. Product category rules for wood and wood-based products for use in construction. European Committee for Standardization, Brussels, Belgium.

Chaussinand, A., Scartezzini, J.L., Nik, V., 2015. Straw bale: a waste from agriculture, a new construction material for sustainable buildings. Energy Procedia 78, 297–302.

Cherubini, F., Guest, G., Strømman, A.H., 2013. Bioenergy from forestry and changes in atmospheric CO2: reconciling single stand and landscape level approaches. J. Environ. Manag. 129, 292–301.

CIRAIG, 2015. Circular economy: a critical literature review of concepts. International Reference Centre for the Life Cycle of Products, Processes and Services (October 2015). www.ciraig.org/pdf/CIRAIG_Circular_Economy_Literature_Review_Oct2015.pdf. (Accessed November 2016).

Citherlet, S., Defaux, T., 2007. Energy and environmental comparison of three variants of a single family house during its whole life span. Build. Environ. 42, 591–598.

CML2 baseline 2000 method, 2000. Centre of Environmental Science. Leiden University, NL. http://www.pre.nl/simapro/impact_assessment_methods.htm.

Construction Products Association, 2012. A Guide to Understanding the Embodied Impacts of ConstructionProducts.http://www.constructionproducts.org.uk/publications/sustainability/a-guide-to-understanding-the-embodied-impacts-of-construction-products/. (accessed November 2016).

Cuéllar-Franca, R.M., Azapagic, A., 2012. Environmental impacts of the UK residential sector: life cycle assessment of houses. Build. Environ. 54, 86–99.

De la Cruz, F.B., Chanton, J.P., Barlaz, M.A., 2013. Measurement of carbon storage in landfills from the biogenic carbon content of excavated waste samples. Waste Manag. 33, 2001–2005.

DHUP, 2013. French National Decree on the Environmental Declaration of All Construction Products. http://ftp.grenoble.cstb.fr/Public/Fouquet/Proceedings-Avnir/divers/Posters/Construction/251_Roy.pdf. (accessed November 2016).

Dias, A.C., Arroja, L., 2012. Environmental impacts of eucalypt and maritime pine wood production in Portugal. J. Clean. Prod. 37, 368–376.

Ding, C.K.C., 2008. Sustainable construction: the role of environmental assessment tools. J. Environ. Manag. 86, 451–464.

dos Santos, M.F.N., Battistelle, R.A.G., Bezerra, B.S., Varum, H.S.A., 2014. Comparative study of the life cycle assessment of particleboards made of residues from sugarcane bagasse (Saccharum spp.) and pine wood shavings (Pinus elliottii). J. Clean. Prod. 64, 345–355.

Ellen MacArthur Foundation, 2015. http://www.ellenmacarthurfoundation.org. (accessed March 2016).

European Commission, 2010. Commission decision on establishing the ecological criteria for the award of the Community Ecolabel for wooden floor coverings. Official Off. J. Eur. Union 2010/18/EC. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010D0018&from=EN.

European Commission, 2012. Innovating for Sustainable Growth—A Bioeconomy for Europe. European Commission, Brussels.

European Commission, 2016. Horizon 2020—The EU Framework Programme for Research and Innovation—Bioeconomy. http://ec.europa.eu/programmes/horizon2020/en/h2020-section/bioeconomy. (accessed March 2016).

Fahnestock, J., 2016a. The use of concept related to sustainable development in political and strategic documents. Deliverable 2.1 in the project European Global Transitional Network on Eco-Innovation, Green Economy and Sustainable Development. Innovation for Sustainable Development Network, Centre for European Economic Research (ZEW), Mannheim, Germany, 39 p.

Fahnestock, J., 2016b. Personal communication, March.

Fearnside, P., 2002. Why a 100-year time horizon should be used for global warming mitigation calculations. Mitig. Adapt. Strateg. Glob. Chang. 7, 19–30.

Ferreira J., Esteves B., Nunes L., Domingos I., 2016. Life cycle assessment of thermally treated and untreated maritime pine boards: a Portuguese case study. Int. Wood. Products J. 7 (3), 124–129.

Frischknecht, R., Althaus, H.-J., Bauer, C., Doka, G., Heck, T., Jungbluth, N., Kellenberger, D., Nemecek, T., 2007. The environmental relevance of capital goods in life cycle assessments of products and services. Int. J. Life Cycle Assess. 12, 7–17.

Ganne-Chédeville, C., Diederichs, S., 2015. Potential environmental benefits of ultralight particleboards with biobased foam cores. Int. J. Polym. Mater. 2015, 1–14.

González-García, S., Feijoo, G., Widsten, P., et al., 2009. Environmental performance assessment of hardboard manufacture. Int. J. Life Cycle Assess. 14, 456–466.

González-García, S., Dias, A.C., Arroja, L., 2013. Life-cycle assessment of typical Portuguese cork oak woodlands. Sci. Total Environ. 452–453, 355–364.

Gorse, C., Thomas, F., Glew, D., Miles Shenton, D., 2016. Achieving sustainability in new build and retrofit: building performance and life cycle analysis. In: Dastbaz, M., et al. (Eds.), Building Sustainable Futures. Springer International Publishing, Basel, http://dx.doi.org/10.1007/978-3-319-19348-9_8.

Gustavsson, L., Sathre, R., 2006. Variability in energy and carbon dioxide balances of wood and concrete building materials. Build. Environ. 41, 940–951.

Gustavsson, L., Joelsson, A., Sathre, R., 2010. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energ. Buildings 42, 230–242.

Haapio, A., Viitaniemi, P., 2008. A critical review of building environmental assessment tools. Environ. Impact Assess. Rev. 28, 469–482.

Hardy, R.W.F., 2002. The bio-based economy. In: Janick, J., Whipkey, A. (Eds.), Trends in New Crops and New Uses. ASHS Press, Alexandria, VA, pp. 11–16.

He, Z., Zhang, Y., Wei, W., 2012. Formaldehyde and VOC emissions at different manufacturing stages of wood-based panels. Build. Environ. 47, 197–204.

Henry, B., 2012. Understanding the Environmental Impacts of Wool: A Review of Life Cycle Assessment Studies—A Report Prepared for Australian Wool Innovation & International Wool Textile Organisation. Agri Escondo Pty Ltd, IWTO, Brussels, Belgium, 58 p.

Hill, C.A.S., 2006. Wood Modification: Chemical, Thermal and Other Processes. John Wiley & Sons Ltd, Chichester, UK. ISBN: 978-0-470-02172-9. http://dx.doi.org/10.1002/0470021748.

Hill, C., Norton, A., 2014. The environmental impacts associated with wood modification balanced by the benefits of life extension. In: European Conference on Wood Modification 2014. pp. 8.

Hingston, J.A., Collins, C.D., Murphy, R.J., Lester, J.N., 2001. Leaching of chromated copper arsenate wood preservatives: a review. Environ. Pollut. 111, 53–66.

Hollberg, A., Ruth, J., 2016. LCA in architectural design—a parametric approach. Int. J. Life Cycle Assess. 21 (7), 943–960. http://dx.doi.org/10.1007/s11367-016-1065-1.

Hopfe, C.J., Augenbroe, G.A., Hensen, L.M., 2013. Multi-criteria decision making under uncertainty in building performance assessment. Build. Environ. 69, 81–90.

Ingrao, C., Bacenetti, J., Bezama, A., Blok, V., Geldermann, J., Goglio, P., et al., 2016. Agricultural and forest biomass for food, materials and energy: bio-economy as the cornerstone to cleaner production and more sustainable consumption patterns for accelerating the transition towards equitable, sustainable, post fossil-carbon societies. J. Clean. Prod. 117, 4–6.

IPCC, 2007. Climate change 2007: synthesis report. In: Pachauri, R.K., Reisinger, A. (Eds.), Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Core Writing Team. IPCC, Geneva, Switzerland, 104 pp. www.ipcc.ch/report/ar4.

IPCC, 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., et al. (Eds.), Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York, NY. www.ipcc.ch/report/ar5/wg1.

IPCC, 2014. Climate change 2014: synthesis report. In: Core Writing Team, R.K., Pachauri, Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151 p. www.ipcc.ch/report/ar5/syr.

ISO, 2000. ISO 14020:2000. Environmental Labels and Declarations—General Principles. International Organization for Standardization, Geneva, Switzerland.

ISO, 2004. ISO 14024:2004. Environmental Labels and Declarations—Type 1 Environmental Labelling—Principles and Procedures. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006a. ISO 14025:2006. Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006b. ISO 14040:2006. Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006c. ISO 14044:2006. Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland.

ISO, 2007. ISO 21930:2007. Sustainability in Building Construction—Environmental Declaration of Building Products. International Organization for Standardization, Geneva, Switzerland.

ISO, 2010. ISO 21931-1:2010. Sustainability in Building Construction—Framework for Methods of Assessment of the Environmental Performance of Construction Works—Part 1: Buildings. International Organization for Standardization, Geneva, Switzerland.

ISO, 2016. ISO 14021:2016. Environmental Labels and Declarations—Self-Declared Environmental Claims (Type II Environmental Labelling). International Organization for Standardization, Geneva, Switzerland.

Jones, A.K., Jones, D.L., Cross, P., 2014. The carbon footprint of lamb: sources of variation and opportunities for mitigation. Agric. Syst. 123, 97–107.

Kellenberger, D., Althaus, H.-J., 2009. Relevance of simplifications in LCA of building components. Build. Environ. 44, 818–825.

Kuittinen, M., Ludvig, A., Weiss, G., 2013. Wood in Carbon Efficient Construction; Tools, Methods and Application. CEI-Bois, Brussels, Belgium, 163 p.

Lasvaux, S., Gantner, J., Wittstock, B., Bazzana, M., Schiopu, N., Saunders, T., Gazulla, C., Mundy, J.A., Sjöström, C., Fullana-i-Palmer, P., Barrow-Williams, T., Braune, A., Anderson, J., Lenz, K., Takacs, Z., Hans, J., Chevalier, J., 2014a. Achieving consistency in life cycle assessment practice within the European construction sector: the role of the EeBGuide InfoHub. Int. J. Life Cycle Assess. 19, 1783–1793.

Lasvaux, S., Ventura, A., Habert, G., De La Roche, C., Hermel, K., Feraille, A., Tardivel, Y., Tessier, C., 2014b. Linking research activities and their implementation in practice in the construction sector: the LCA construction 2012 experience. Int. J. Life Cycle Assess. 19, 463–470.

Lasvaux, S., Habert, G., Peuportier, B., Chevalier, J., 2015. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. Int. J. Life Cycle Assess. 20, 1473–1490.

Levasseur, A., Lesage, P., Margni, M., Samson, R., 2013. Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. J. Ind. Ecol. 17, 117–128.

Marland, E., Marland, G., 2003. The treatment of long-lived, carbon-containing products in inventories of carbon dioxide emissions to the atmosphere. Environ. Sci. Pol. 6, 139–152.

Marland, E., Stellar, K., Marland, G., 2010. A distributed approach to accounting for carbon in wood products. Mitig. Adapt. Strateg. Glob. Chang. 15, 71–91.

Menet, J.L., Gruescu, I.C., 2012. A comparative life cycle assessment of exterior walls constructed using natural insulation materials. Environ. Eng. Sust. Dev. Entrep. 1 (4), 14.

Moura-Costa, P.H., Wilson, C., 2000. An equivalence factor between CO2 avoided emissions and sequestration-description and applications in forestry. Mitig. Adapt. Strateg. Glob. Chang. 5, 51–60.

Murphy, R.J., Norton, A., 2008. Life cycle assessments of natural fibre insulation materials final report. In: 11th Int. Conf. Non-Conventional Mater Technol NOCMAT 2009. University of Bath, Bath, UK, 79.

Nabuurs, G.J., Pussinen, A., Karjalainen, T., Erhard, M., Kramer, K., 2002. Stemwood volume increment changes in European forests due to climate change-a simulation study with the EFISCEN model. Glob. Chang. Biol. 8, 304–316.

Nässén, J., Hedenus, F., Karlsson, S., Holmberg, J., 2012. Concrete vs. wood in buildings—an energy system approach. Build. Environ. 51, 361–369.

Newsham, G.R., Mancini, S., Birt, B.J., 2009. Do LEED-certified buildings save energy? Yes, but…. Energy Build. 41, 897–905.

NF, 2004. NF P01-010: 2004. Qualité environnementale des produits de construction - Déclaration environnementale et sanitaire des produits de construction. AFNOR, Paris, France. https://www.boutique.afnor.org/norme/nf-p01-010/qualite-environnementale-des-produits-de-construction-declaration-environnementale-et-sanitaire-des-produits-de-construction/article/663460/fa136284.

Norgate, T., Haque, N., 2010. Energy and greenhouse gas impacts of mining and mineral processing operations. J. Clean. Prod. 18, 266–274.

Ortiz, O., Pasqualino, J.C., Castells, F., 2010. The environmental impact of the construction phase: an application to composite walls from a life cycle perspective. Resour. Conserv. Recycl. 54, 832–840.

Pajchrowski, G., Noskowiak, A., Lewandowska, A., Strykowski, W., 2014. Wood as a building material in the light of environmental assessment of full life cycle of four buildings. Constr. Build. Mater. 52, 428–436.

Palumbo, M., 2015. Contribution to the development of new bio-based thermal insulation materials made from vegetal pith and natural binders (PhD thesis). Universitat Politècnica de Catalunya, 187 p.

Pargana, N., Pinheiro, M., Silvestre, J., Brito, J., 2014. Comparative environmental assessment of thermal materials of buildings. Energy Build. 82, 466–481.

Passer, A., Kreiner, H., Maydl, P., 2012. Assessment of the environmental performance of buildings: a critical evaluation of the influence of technical building equipment on residential buildings. Int. J. Life Cycle Assess. 17, 1116–1130.

Passer, A., Lasvaux, S., Allacker, K., De Lathauwer, D., Spirinckx, C., Wittstock, B., Kellenberger, D., Gschösser, F., Wall, J., Wallbaum, H., 2015. Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. Int. J. Life Cycle Assess. 20, 1199–1212.

Pearce, D.W., Turner, R.K., 1989. Economics of Natural Resources and the Environment. Johns Hopkins University Press, Baltimore, MD.

Penaloza, D., Sandin, G., Røyne, F., 2016. The influence of system boundaries and baseline in climate impact assessment of forest products. J. Clean. Prod. 116, 90–99.

Pilli, R., Fiorese, G., Grassi, G., 2015. EU mitigation potential of harvested wood products. Carbon Balance Manage. 10, 6.

Pizzi, A., 2008. Tannins: major sources, properties and applications. In: Naceur Belgacem, M., Gandini, A. (Eds.), Monomers, Polymers and Composites from Renewable Resources. Elsevier, London, UK, pp. 179–199. ISBN: 978-0-08-045316-3.

PRé Consultants, 2010. Impact Assessment Methods. http://www.pre.nl/simapro/impact_assessment_methods.htm#EP97. (accessed 01.04.16).

Rivela, B., Hospido, A., Moreira, T., Feijoo, G., 2005. Life cycle inventory of particleboard: a case study in the wood sector. Int. J. Life Cycle Assess. 11, 106–113.

Robertson, G.P., Collins, S.L., Foster, D.R., Brokaw, N., Ducklow, H.W., Gragson, T.L., Gries, C., Hamilton, S.K., McGuire, A.D., Moore, J.C., Stanley, E.H., Waide, R.B., Williams, M.W., 2012. Long-term ecological research in a human-dominated world. Bioscience 62, 342–353.

Roffael, E., 2006. Volatile organic compounds and formaldehyde in nature, wood and wood based panels. Holz Roh Werkst. 64, 144–149.

Roodman, D.M., Lenssen, N., 1995. A building revolution: how ecology and health concerns are transforming construction. Worldwatch Paper #124, ISBN: 1-878071-25-4.

Røyne, F., Peñaloza, D., Sandin, G., Berlin, J., Svanström, M., 2016. Climate impact assessment in life cycle assessments of forest products: implications of method choice for results and decision-making. J. Clean. Prod. 116, 90–99.

Salazar, J., Meil, J., 2009. Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. J. Clean. Prod. 17 (17), 1563–1571.

Sandin, G., Peters, G.M., Svanström, M., 2014. Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling. Int. J. Life Cycle Assess. 19 (4), 723–731.

Sathre, R., González-García, S., 2014. Life cycle assessment (LCA) of wood-based building materials. In: Pacheco-Torgal, F., Cabeza, L.F., Labrincha, J., de Magalhaes, A.G. (Eds.), Eco-Efficient Construction and Building Materials. Woodhead Publishing (Elsevier), London, UK, pp. 311–337.

Sathre, R., Gustavsson, L., 2009. Using wood products to mitigate climate change: external costs and structural change. Appl. Energy 86, 251–257.

Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: policies and facts. Environ. Dev. 16, 3–34.

Schmidt, A.C., Jensen, A.A., Clausen, A.U., et al., 2004. A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Int. J. Life Cycle Assess. 9, 122–129.

Shirley, K., Marland, E., Cantrell, J., Marland, G., 2011. Managing the cost of emissions for durable, carbon-containing products. Mitig. Adapt. Strateg. Glob. Chang. 16, 325–346.

Sierra-Pérez, J., Boschmonart-Rives, J., Dias, A.C., Gabarrell, X., 2016. Environmental implications of the use of agglomerated cork as thermal insulation in buildings. J. Clean. Prod. 126, 97–107.

Silva, D.A.L., Lahr, F.A.R., Garcia, R.P., Freire, F.M.C.S., Ometto, A.R., 2013. Life cycle assessment of medium density particleboard (MDP) produced in Brazil. Int. J. Life Cycle Assess. 18, 1404–1411.

Silva, D.A.L., Lahr, F.A.R., Pavan, A.L.R., et al., 2014. Do wood-based panels made with agro-industrial residues provide environmentally benign alternatives? An LCA case study of sugarcane bagasse addition to particle board manufacturing. Int. J. Life Cycle Assess. 19 (10), 1767–1778.

Sinha, A., Knowles, C., 2014. Green building and the global forest sector. In: Hansen, E., Panwar, R., Vlosky, R. (Eds.), The Global Forest Sector: Changes, Practices, and Prospects. CRC Press, Boca Raton, FL; London; New York, NY, pp. 261–280.

Sinha, A., Kutnar, A., 2012. Carbon footprint versus performance of aluminum, plastic, and wood window frames from cradle to gate. Buildings 2, 542–553.

Soimakallio, S., Cowie, A., Brandão, M., Finnveden, G., Ekvall, T., Erlandsson, M., Koponen, P., Karlsson, P.-E., 2015. Attributional life cycle assessment: is a land-use baseline necessary? Int. J. Life Cycle Assess. 20, 1364–1375.

SPF Santé Publique, 2015. Health, food chain safety and environment. The Belgian Framework for Environment Messages Concerning Construction Products and Environmental Product Declarations (EPD). Federal Public Service (FPS) Health, Food Chain Safety and Environment, Brussels, Belgium. www.health.belgium.be/fr/le-cadre-belge-pour-les-messages-environnementaux-sur-les-produits-pour-la-construction-et-les#Document. (accessed November 2016).

Stahel, W.R., Reday-Mulvey, G., 1981. Jobs for Tomorrow, the Potential for Substituting Manpower for Energy. Vantage Press, New York, NY.

Stevanović, S., 2013. Optimization of passive solar design strategies: a review. Renew. Sustain. Energy Rev. 25, 177–196.

van Dam, J.E.G., Bos, H.L., 2004. The Environmental Impact of Fibre Crops in Industrial Applications. Food and Agriculture Organization, Rome.

van der Lugt, P., van den Dobbelsteen, A.A.J.F., Janssen, J.J.A., 2006. An environmental, economic and practical assessment of bamboo as a building material for supporting structures. Constr. Build. Mater. 20, 648–656.

VINNOVA, 2013. A Bio-Based Economy—A Strategic Research and Innovation Agenda for New Businesses. http://www.vinnova.se/PageFiles/751324632/A%20BIO-based%20Economy.pdf. (accessed March 2016).

Werner, F., Richter, K., 2007. Wood building products in comparative LCA: a literature review. Int. J. Life Cycle Assess. 12 (7), 470–479.

Wilson, J.B., 2009. Life-cycle inventory of particleboard in terms of resources, emissions, energy and carbon. Wood Fiber Sci. 42, 90–106.

Wolf, M.-A., Pant, R., Chomkhamsri, K., Sala, S., Pennington, D., 2012. International Reference Life Cycle Database (ILCD) Handbook—Towards More Sustainable Consumption and Production for a Resource Efficient Europe. Joint Research Centre, Luxembourg Publications Office of the European Union, Luxembourg.

Yuan, Z., Bi, J., Morgiguchi, Y., 2008. The circular economy: a new development strategy in China. J. Ind. Ecol. 10 (1–2), 4–8.

Zhijun, F., Nailing, Y., 2007. Putting circular economy into practice in China. Sustain. Sci. 2, 95–101.

This page intentionally left blank

Durability, efficacy and performance of bio-based construction materials: Standardisation background and systems of evaluation and authorisation for the European market

10

M. Kutnik[*], *E. Suttie*[†], *C. Brischke*[‡,§]
[*]Technological Institute FCBA, Bordeaux, France, [†]BRE, Watford, United Kingdom, [‡]Leibniz University Hannover, Hannover, Germany, [§]University of Göttingen, Göttingen, Germany

10.1 European standardisation of durability and performance

10.1.1 Introduction

Standardisation is an important tool for improving product quality and reliability, facilitating harmonisation of the industry and strengthening consumer confidence. The foremost aim of European standardisation is to facilitate the exchange of quality-assured goods and services with identified characteristics through the elimination of technical barriers to trade. The recognition and use of standards by the industry and social and economic partners is mostly voluntary. However, European standards are sometimes related to European legislation (directives and regulations), and conformity to such standards may constitute a legal requirement that must be met by manufacturers before certain products can be traded legally.

Bio-based forestry and agriculture products have a long history of application. Many of such products are part of our everyday life, such as paper, cardboard or chemicals used for self-care. However, the last few decades have seen the emergence of new bio-based products intended for other applications, including construction products. The reasons for the growing interest within the building sector in the use of bio-based products are related, among others, to their positive environmental impact and to the new functionalities they may provide to building products.

In line with the EU's innovation strategy and following the initiation of a new policy in 2006 that aims to support the development of high economic and societal value markets, the European Commission has proposed further steps for the creation of lead markets (COM [2007] 860), developing bio-based products being one of them. Acknowledging

Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00010-0
© 2017 Elsevier Ltd. All rights reserved.

the fact that standards may facilitate the development of lead markets and thus the need for common standards for such products, the European Commission issued the mandate M/492 to CEN, CENELEC and ETSI to implement and elaborate a standardisation programme for bio-based products. This decision resulted in 2011 with the creation of the technical committee CEN/TC 411 'Bio-based products' dedicated to the development of the European market for bio-based products, with a focus on bio-based products other than food, feed and biomass for energy applications. The CEN Technical Committees developing standards in the area of other bio-based products are CEN/TC 19, Gaseous and liquid fuels, lubricants and related products of petroleum, synthetic and biological origin; CEN/TC 249, Plastics; and CEN/TC 276, Surface active agents.

Additionally, the standardisation work related to the durability, protection and performance of the specific types of bio-based products being wood and wood-based materials is managed by the European Technical Committee CEN/TC 38 'Durability of wood and wood-based products', created in 1965. So far, some fifty standards have been adopted by CEN/TC 38, dealing with aspects related to terminology, general concepts such as wood natural durability (EN 350, CEN, 2016b) and use classes (EN 335, CEN, 2013a), testing and evaluation of wood preservatives, analytical methods, biological tests, classifications and specifications in accordance with the market needs and European regulations. Political, economic, social, technical, legal and international factors either directly prompt the standardisation activities proposed by CEN/TC 38 or at least significantly influence them.

Finally, the evaluation of the characteristics and performance of several specific bio-based materials used in the construction sector can also be handled by other committees so-called product CEN/TCs, slightly different from TC 411 and TC 38, the scope of which is transversal over several other TCs. For example, Technical Committee CEN/TC 88 'Insulation materials' developed the standard EN 15101-1 (CEN (2014b)) 'Thermal insulation products for buildings—In situ formed loose fill cellulose (*LFCI*) products—Part 1: Specification for the products before installation' that includes a specific annex on the evaluation of resistance against mould growth of cellulose-based insulation materials (Annex F: Method for determining mould fungi resistance). Another example is a standard meant for the assessment of biological durability of plywood (CEN/TS 1099, CEN, 2007), prepared by Technical Committee CEN/TC 112 'Wood-based panels'.

At the international level, an ISO Technical Committee (ISO/TC 296) was created in 2015 to work specifically on bamboo and rattan. The scope of this committee, chaired by China, is standardisation of bamboo, rattan and bamboo- and rattan-derived materials, including terminology, classification, specifications, test methods and quality requirements. Its aim is to strengthen the global trade in these versatile plants, benefiting businesses and delivering positive gains to the rural communities that depend on their production. So far, there is no related standard published.

10.1.2 Wood and wood-based products

10.1.2.1 CEN/TC 38 'durability of wood and wood-based products': Background and objectives

The main concern of CEN/TC 38 is the durability of wood and wood-based products, but its scope also includes the performance of biocidal products and their processes of

application. These products are used in construction, civil engineering, and furniture production, packaging and other applications. Currently, eight Working Groups (WG 21 to WG 28) are active within CEN/TC 38, each of them dealing with different subjects and work programmes related to biological laboratory and field testing of treated and untreated wood, efficacy assessment criteria, chemical characterisation of products meant for the treatment of wood, environmental issues and service life.

The general objectives of the standards adopted so far include ensuring quality and satisfying consumer expectations, eliminating barriers to trade, harmonising the methods of evaluation used in the sector of wood protection, facilitating understanding between producers and users and providing manufacturers with methods in compliance with legal requirements related to the Construction Product Regulation and the Biocidal Products Regulation (*BPR*). Some specific objectives are also of major importance. These include supporting the utilisation of home-grown and indigenous wood species, promoting sustainable development by delivering reliable wood products with an adequate service life and contributing to a safer construction sector for people and the environment.

The interested sectors are the main chemical manufacturers of active substances and the industry in charge of formulation, wood treaters (including those involved in wood transformation, from sawmilling to manufacturing specific commodities), applicators of treatment and wood industries. Also concerned are installers, users and consumers who use treated and untreated wood extensively for construction, public authorities, institutes, laboratories, consumers' representatives, non-governmental organisations and trade and technical unions and associations. Additionally, partners like architects, prescribers, banks, insurance companies, project contributors and designers are of paramount importance as well.

The benefits of the standardisation in the sector of wood and wood-based products include improved circulation of these products in Europe and increased confidence of users regarding the durability of wood with in-balance efficacy and safety parameters in managing the use of wood and wood-based products, from forest crop to transformation, use, reuse and disposal.

10.1.3 Recent changes and future challenges

The approach to protection, durability and performance of wood and wood-based products changed a lot during the last two decades (Kutnik *et al.*, 2014). New wood-based products, whose durability has been enhanced with the help of non-biocidal innovative processes, entered the wood construction market (e.g. Hill, 2007; Jones, 2012). National forest sectors put many efforts to promote national resources, with the objective of increasing the use of native untreated wood by offsetting low durability through optimised design, adapted to wood products' targeted conditions of use. European regulations also encourage manufacturers to develop products that are more efficient and less harmful to the environment and human health and whose performance takes into account end users' expectations. A gradual shift is discernible in the global approach to durability and performance, which is no longer based only on the inherent characteristics of the material itself but also takes into consideration its interactions with the environment (design, maintenance, exposure and moisture risk).

With new products, processes and construction rules requiring validation tools that could ensure their reliability and future development, CEN/TC 38 is the main source of methods for assessing the characteristics of new wood-based products in this challenging context. However, many improvements and/or amendments of the existing standards are necessary to help the industry adapt to the ongoing changes in the European market because of weaknesses of the standardisation system. For example, most of the current CEN/TC 38 standards are meant for the assessment of the efficacy of wood preservatives and the inherent resistance of wood species and not so much for the assessment of the resistance and performance of new wood-based products whose durability has not been enhanced with the help of biocides (such as thermally modified wood, chemically modified wood, glue-laminated wood, wood-based panels, wood–polymer composites and wood treated with water repellents) and is thus inadequate for their qualification. Another point is that, in their present form, CEN/TC 38 standards almost exclusively consider the material but not the final products (e.g. windows or wooden poles) and thus offer little or no information about the performance of such wood-based products. The general approach to performance focuses mainly on the material's resistance and not on the primary influence of such external factors as moisture risk, design, exposure and maintenance. Biological durability is obviously the key factor determining the performance of wood and wood-based materials in different use classes, but other crucial factors contribute to determining the likelihood of worst-case scenarios occurring in practise, such as those related to exposure, geographical location, moisture risk, maintenance or the presence/absence of wood-destroying agents.

During the last 10 years, utilising the recent scientific, technological and legal developments in the field of wood protection, CEN/TC 38 has worked hard to improve the clarity and the reliability of standards related to wood durability and performance. Recent changes mainly concern a better understanding of the influencing factors and their evaluation.

10.1.3.1 Biological resistance of wood and wood-based products

The natural durability of a wood species is defined as its inherent resistance to wood-destroying agents. It can vary widely depending on the age of the tree, the geographical origin of the tree species and the growing conditions. The European standards EN 350-1 (CEN (1994a)) and EN 350-2 (CEN (1994b)), two of the fundamental standards developed by the CEN/TC 38, have been widely used by the wood industries as the reference documents that provide information on the resistance of wood species. They are used mainly in the construction sector against wood-decay fungi and wood-boring beetles and termites. The standards in question also refer to the related standards for testing these properties of wood and interpreting the results. However, due to certain changes that have occurred in the European market, mainly regarding the diversity of wood-based materials used nowadays, the old EN 350-1 (CEN (1994a)) and EN 350-2 (CEN (1994b)) standards had to undergo a major revision. Among the major changes discussed during the revision of the standard (a process that took many years and was finally completed in 2015), agreement was reached on enlarging the scope of the standard from solid wood to all types of wood-based materials.

The revised standard EN 350 'Durability of wood and wood-based products—Testing and classification of the durability to biological agents of wood and wood-based materials' was published in 2016, superseding EN 350-1 (CEN (1994a)) and EN 350-2 (CEN (1994b)). This European Standard provides guidance on methods for determining and classifying the durability of wood and wood-based materials (defined as 'any processed matrix containing and/or made of a specific percentage of wood') against biological wood-destroying agents. The methods can be applied either to individual wood species, batches of wood or processed wood-based materials. The wood-destroying agents covered in this standard are wood-decay fungi (basidiomycete and soft-rot fungi), beetles capable of attacking dry wood and termites and marine organisms capable of attacking wood in service. Mainly laboratory tests are addressed in the standard as they are more specific because they can be performed under fully controlled conditions. But field tests are taken into consideration as well because they allow determining the durability of a wood species or a wood-based material in different end uses (above-ground and in-ground) exposed to a wide range of wood-destroying organisms and long-term conditioning through weathering. Finally, it is important to point out that treatability, durability to disfiguring fungi, permeability to water and performance in use of wood and wood-based materials are also important issues. However, because standardised methods aiming to assess and classify these factors do not exist and/or have not been extensively experienced yet, only preliminary guidance is given in the standard.

The standard EN 350 (CEN (2016b)) is not meant to test lignocellulosic materials others than wood. Methodological adaptations might be required for testing other organic materials such as bamboo, reed, straw or flax. In practice, many European laboratories have developed adapted test methods since bio-based materials entered the construction market, enabling them to test such materials' resistance to crossing and consumption by termites and degradation by wood-boring insects and wood-decay fungi.

10.1.3.2 Performance

In the context of constantly increasing expectations of customers and end users regarding information about the service life of wood-based products or commodities in real-use conditions (indoor, outdoor, above-ground or in-ground contact, etc.), a specific CEN/TC 38 working group was created in 2010, fully dedicated to this topic (WG 28—'Performance classification'). Indeed, the future of sustainable wood products clearly relies on having a system of standards that can adapt to real-world practise and provide better service life or performance classification information. Moreover, evaluation of the performance of wood and wood-based materials will provide the wood sector with data supporting the seventh essential requirement of the *CPD*/*CPR*.

Performance is defined as the ability of a wood species or a wood-based material to withstand deterioration over time. Performance in service is a combination of parameters fundamentally based on a combination of the durability of the material, its ability to take up and release water (the wetting ability) and the availability of moisture in the end use application. Because wood durability is an important factor that influences the performance and, thus, the service life of a wood product, the standard EN 350 (CEN (2016b)) provides input to service life prediction of wood and wood-based products.

It gives guidance on using wood products appropriate for different end uses and ranks durability against wood-decay organisms of various wood species, thereby allowing species of appropriate durability to be selected for particular uses. However, there are many factors other than durability that influence the service life of a wood-based product, such as good design principles, use conditions, climate and maintenance, which should be taken into consideration.

To determine performance, a relevant test methodology should be selected, which is based on the intended final end use of the product and fits as closely as possible the conditions of real use of the material (e.g. cladding, decking and window joinery). Most notably for products used outdoors, the permeability of the material, the design of the component and its ability to shed water and prevent water trapping and, in some cases, the maintenance of a component or structure can all greatly influence the performance of wood in use.

The major difficulty regarding the assessment of performance is that the development of adequate methods requires models capable of predicting performance in a quantitative and probabilistic format. Performance within a use class may vary depending on geographical location (sometimes even within the same geographical location). This can be due to a number of factors such as difference in biological hazard, climate and microclimate. The relation between performance during testing and in service needs to be quantified in statistical terms and the resulting predictive models need to be calibrated to provide a realistic measure of service life, including a defined acceptable risk of non-conformity.

Performance can be determined either by an adequate set of laboratory tests including relevant ageing procedures or by field tests simulating in-service conditions. If field test data are available, they shall take precedence over the data from laboratory tests. If no data from field tests are available, a provisional classification using the data from laboratory tests is acceptable. EN 252 (CEN (2014e)) provides a method that can be adapted to assess the performance of wood and wood-based materials to withstand biodeterioration (wood-decay fungi and subterranean termites) over time. The principle of the test consists in half-burying stakes manufactured with the material to be tested in the ground of an experimental field, alongside with stakes made of a non-resistant wood species used as references. Comparison between the time before failure of the wood-based material under test and a reference wood species or material can be a possible assessment criterion. However, no single reference test protocol has been designed so far.

10.1.3.3 The moisture risk as a factor influencing performance

The penetration of water into wood when exposed to humidity and the rate of release when wood is allowed to dry can supply relevant information regarding its expected service life, mainly in situations of use where wood is exposed to significant amounts of moisture, for instance, when used outdoors. The combination of water uptake and release, taking into account time as a critical factor, allows for predicting the time of wetness of a wood-based product in service and as such provides a parameter indicating how prone it is to fungal decay. This parameter can also be called moisture resistance and can be regarded as a being complementary to biological durability based on the

presence of components preventing the development of wood-decay fungi. Time of wetness is affected by environmental parameters, including design, building physics, exposure and maintenance, which vary greatly across Europe and may have a remarkable impact on performance. No internationally agreed methods for assessing these parameters have been developed so far (Meyer *et al.*, 2014; Meyer-Veltrup *et al.*, 2016), but various national approaches based on experience take these parameters into account.

Because permeability to water is one of the key factors affecting the performance of a wooden component as it conditions the possibilities of fungal decay, one may assume that wood species with lower levels of permeability to water will perform better than others that have the same level of natural durability to wood-decay fungi. Consequently, wood species that are less permeable to water are expected to perform better than permeable species when wood is exposed to intermittent wetting. This might be due to naturally occurring extractives, through thermal or chemical cell wall modification or through impregnation with water repellents. Intercomparison tests were initiated in 2013 in the framework of the PerformWOOD research project ('Performance standards for wood in construction—delivering customer service life needs'—EC FP7 Grant Agreement 319132) to compare different methods applied both across Europe and at the national level to measure wood's permeability to water, and their results were used in setting up the standard prEN 16818 (CEN (2016e)). The method described in this standard allows for testing the permeability to water of a wood-based material but other standardised tests developed for coated wood, such as EN 927-5 (CEN (2006)) and ISO 535 (ISO (2014b)), can also be used for measuring wood's permeability to liquid water.

10.1.3.4 Durability to disfiguring fungi

Wood-disfiguring fungi (blue stain and moulds) are of economic importance as they affect the aesthetic appearance of wood and other bio-based materials in service. Durability against blue stain varies between wood species, while susceptibility to mould growth depends less on the botanic species and is more related to environmental factors influencing the moisture content of the material, such as condensation. These organisms normally have no direct significant effect on the mechanical resistance of wood, but abnormal levels of humidity promoting their development can possibly affect the inherent properties of other bio-based materials.

There are few methods allowing testing durability to disfiguring fungi. The laboratory test method described in the standard EN 152 (CEN (2012)), originally designed to assess the effectiveness of a wood preservative in preventing the development of blue stain fungi in wood in service, can be adapted for the assessment of biological durability against blue stain. No CEN standards allowing for the assessment of resistance against mould fungi exist; however, several national methods are in use, for example, NF X 41-547 (1992) and BS 3900-G6 (1989).

10.1.3.5 Service life planning

CEN/TC 38, and particularly the work of WG 28, has a liaison with standardisation activity in the field of buildings and civil engineering works. This is primarily with the ISO/TC 59/SC14 secretariat who are responsible for standards for buildings including

general rules for performance requirements, including functional and user requirements related to service life, sustainability, accessibility and usability. The design life of buildings covers standardisation within this subject field from terminology to life cycle costing, durability, maintenance, performance audits to data requirements and procedures.

The ISO 15686 series of standards are under the direct responsibility of ISO/TC 59/SC 14, which includes

- ISO 15686-2 (ISO (2012)) Buildings and constructed assets—Service life planning—Part 2: Service life prediction procedures.
- ISO 15686-4 (ISO (2014a)) Building construction—Service life planning—Part 4: Service life planning using building information modelling.
- ISO 15686-7 (ISO (2006)) Buildings and constructed assets—Service life planning—Part 7: Performance evaluation for feedback of service life data from practice.
- ISO 15686-8 (ISO (2008)) Buildings and constructed assets—Service life planning—Part 8: Reference service life and service life estimation.

10.1.4 Bio-based products

10.1.4.1 CEN/TC 411 'bio-based products': Background, objectives, challenges

The term bio-based product refers to products wholly or partly derived from biomass, such as plants, trees or animals, which may have undergone physical, chemical or biological treatment. Bio-based products are considered to be of high societal and economic interest due to several positive factors, such as the promotion of the use of renewable and expendable resources, reduced dependency on the limited and increasingly expensive fossil resources, the potential to reduce greenhouse gas emissions (carbon neutral/low carbon impact), the potential for sustainable industrial production, the positive impact on populations health, the promotion of rural development and increased industrial competitiveness through innovative ecoefficient products.

10.1.4.2 Scope of CEN/TC 411

The aim of the CEN Technical Committee CEN/TC 411 'Bio-based products' is to develop standards concerning terminology, methods, criteria, guidance and tools (on, for instance, product declarations), applicable to bio-based products and standards for horizontal aspects, including sampling, bio-based content, application of LCA, sustainability criteria for biomass and final products and end-of-life and bio-based (carbon) content. CEN/TC 411 also intends to develop a certification scheme (or schemes) for bio-based products, identifying which characteristics can or should be assessed and how they should be reported. These standards will play an important role in the uptake of bio-based products, both in consumer markets and in public procurement, by enabling clear communication about the benefits of bio-based products. Major standardisation needs concern the determination of bio-based content (carbon and biomass), product functionalities and biodegradability.

CEN/TC 411 is a group that was created by CEN in Jan. 2009 to produce an overview of already existing standards on all types of bio-based products, to identify the needs for pre- and conormative research relevant to the development of European standards or other standardisation deliverables and to produce recommendations for a standardisation work programme. The work done by CEN/TC 411 takes into account the Mandate M/492 and the final report of the Technical Board Working Group, CEN/BT/WG 209 'Bio-based products'.

10.1.4.3 Prestandardisation project KBBPS 'knowledge based bio-based products'

CEN/BT/WG 209 pointed out the fact that, given how relatively young and complex the sector of bio-based products is, reliable standards are needed to serve as guidelines for the industry, policy makers or consumers. The KBBPS project was created in order to tackle this deficiency. Led by the Netherlands Standardisation Institute (NEN), KBBPS project FP7/2007-2013 (under grant agreement no. KBBE/FP7EN/312060/'KBBPPS') is focusing on prestandardisation research for bio-based products. The results are automatically fed into the CEN standardisation process on the same topic. Planned for 3 years, the project aimed to investigate testing methods for a variety of bio-based products that focus on biomass content, bio-based carbon content, biodegradability and functionality. The goal was to integrate the results of this research into further standardisation work conducted by CEN (and possibly other international standardisation bodies) and to provide the European and global market with horizontal standards on bio-based carbon content, biomass content and biodegradability that have been assessed on a set of different products, such as solvents, plastics and lubricants. The final results of the project were presented in 2015. CEN/TS 16640 (CEN (2014a)) 'Bio-based products—Determination of the bio-based carbon content of products using the radiocarbon method' was the first project result officially adopted into a standard.

10.1.4.4 Determination of the bio-based content: A key question

As has already been mentioned, the development of a standard test method for bio-based carbon content measurements in different bio-based products was the subject of the investigations within the framework of the KBBPS project, with the aim of setting up a universal method applicable to various products and allowing both the producers and the consumers of the products to evaluate the bio-based content in their products.

The extent to which a product is derived from biomass is characterised by its bio-based carbon content. Generally, the bio-based carbon content and the total bio-based content (not only carbon but also oxygen and/or hydrogen and/or nitrogen can be bio-based) are expressed as a fraction of the biogenic carbon (^{14}C) to the total amount of carbon in the product. But, since the ^{14}C isotope is not stable and undergoes radioactive decay, with the half-period of approximately 5730 years, it is absent in old fossil products and is present only in products developed from recent biomass.

The procedure for determining the bio-based carbon content was proposed and validated by interlaboratory testing in CEN/TS 16640 (CEN (2014a)). This standard describes the complete method that is recommended to be used for the conversion of samples for ^{14}C analysis. The method is based on the complete combustion of the samples and collection of the CO_2 that is released during the combustion process. The collected CO_2 is then analysed for the ^{14}C content. However, recent work demonstrated that applying CEN/TS 16640 (CEN (2014a)) and elementary analysis of C, O, H and N from wood-based panels is not easy and suggests to apply preferentially EN 16785-1 (CEN (2015a)) and EN 16785-2 (CEN (2016a)) to calculate the flow rate (input and output) of wood and other materials in a process and to assess the bio-based content based by calculation.

However, in some cases, the bio-based content of a product can differ substantially from the bio-based carbon content, when other elements derived from biomass are present in higher levels than carbon. Since in Europe the industry is concerned about presenting the total biomass content, which cannot generally be declared on the basis of bio-carbon content alone, there is a need to develop other techniques and standard test methods and testing schemes for determining biomass content that are not solely dependent on ^{14}C analysis.

Work made by the CEN/TC 411 Bio-based products has recently appeared in relationship with the CEN/TC 38, regarding the aspects of measurement of biogenic carbon and more largely the promotion of wood and wood-based materials.

10.1.4.5 Overview of the existing methods of evaluation set up by CEN/TC 411

Five CEN/TC 411 Working Groups (WP) are currently active and work on developing European Standards and other standardisation deliverables. So far, the documents that have been or are being developed in relation to the following horizontal aspects of bio-based products concern common terminology (EN 16575, CEN, 2014d), methods for determining bio-based content (CEN/TR 16721, CEN, 2014a; CEN/TS 16640, CEN, 2014f; EN 16785-1, CEN, 2015a), sustainability aspects (EN 16751, CEN, 2016d), life cycle assessment (EN 16760, CEN, 2015b) and declaration tools applicable to bio-based products identifying which characteristics can/should be assessed and how they should be reported.

10.1.5 Biological durability of bio-based products

10.1.5.1 Resistance against moulds

Due to their positive environmental attributes and their performance, the use of bio-based insulation materials such as wood fibre, loose fill cellulose, hemp, flax and straw has been increasing in the construction industry across Europe. However, despite the environmental assets and performance characteristics of these materials, more evidence is needed that they are able to resist to moulds, that is, aerobic fungi that require water and organic and mineral compounds to grow (Botton *et al.*, 1990). Experience has shown that the water content in the product is the crucial parameter influencing fungal growth. Moulds can easily grow on insulation materials if hygroscopic

conditions are favourable. In the indoor environment, most construction materials can be contaminated by mould fungi if relative humidity exceeds 65%–70% (Flannigan *et al.*, 1996, Botton *et al.*, 1990).

Different non-European standardised test methods have been used for many years to assess resistance against moulds, such as ISO 846 (ISO (1997b)), CUAP (2009) and ASTM C1338 (ASTM (2008)). However, these methods exhibit several drawbacks that limit their reliability in assessing the resistance against moulds of bio-based products (e.g. lack of control of the test material's relative humidity or of quantitative assessment of the mould growth). EN15101-1 (CEN (2014b)) is the first harmonised standard for which a method of determining mould resistance is implemented. However, the method described in Annex F of this standard was found unreliable by several European test laboratories using it because resistance against moulds was determined only by visual assessment, leading to a considerable risk of errors. It has been agreed that a quantitative method is necessary in order to assess precisely the amount of fungal spores developing on the test material and to draw conclusions about whether it is resistant against mould growth. A European round robin test is currently under way within the framework of CEN/TC 88/WG 15, with the aim of improving the current EN 15101-1 standard (CEN (2014b)).

10.1.5.2 Resistance against other biological agents

Testing the resistance of bio-based products against biological agents is in the scope of very few European standards.

The standard EN 15534-1 (CEN (2014c)) worked out by CEN/TC 249 'Plastics' specifies test methods for the determination of the properties of composites made from cellulose-based materials and thermoplastics, usually called wood–polymer composites (*WPC*) or natural fibre composites (*NFC*). This part of EN 15534 is applicable to cellular or non-cellular compounds and products, made from cellulose-based materials and thermoplastics, processable using plastics processing techniques and without a threshold for the cellulose-based material content. The standard describes protocols and gives guidance for testing biological durability against wood-decay fungi, disfiguring fungi, algae and termites.

CEN/TC 175 'Round and sawn timber' is currently working on the prEN 17009 (CEN (2016c)) standard 'Flooring of lignified materials other than wood—Characteristics, evaluation of conformity and marking', which includes an annex on biological durability testing of products made of lignified materials other than wood. This standard defines and specifies the relevant characteristics, requirements and appropriate test methods for the determination of the suitability of floorings made with at least a top layer of lignified materials other than wood (bamboo and palm flooring products) for use as internal flooring, which may or may not be treated to improve their reaction to fire performance or their durability against biological agents. If no specific data on biological durability are available, products covered by this standard may be assigned preliminarily not durable without further testing. If a higher durability is required or shall be declared, biological durability shall be determined. As long as no specific durability test methods for lignified materials other than wood are available, this standard recommends adapting and using existing testing protocols for wood and wood-based products.

Test methods of assessing the resistance of textile materials (which can be part of bio-based products such as insulation) against microbiological attack (bacteria and fungi) are in the scope of the work done by CEN/TC 248 'Textiles and textile products'. This CEN committee has developed and validated through round robin tests the protocol described in the standard EN 14119 (CEN (2003a)) 'Testing of textiles—Evaluation of the action of microfungi'. This standard specifies a method for determining long-term resistance of textiles to attack by microorganisms/mixed cultures. In this method, samples are subjected to microbiological attack and subsequently visually examined. Additionally, the international standard ISO 3998 (ISO (1977a)) specifies a method for the determination of the resistance to the larvae of certain insects of textiles containing animal fibres in any proportion. This standard is applicable to all textiles. The mass loss of all specimens and the condition of the test larvae are determined to assess the resistance of each test specimen.

10.2 EC regulations related to wood-based and other construction products

The construction sector is under pressure to improve its cost-effectiveness, quality, energy efficiency and environmental performance and to reduce the use of non-renewable resources. A key issue for the competitiveness of bio-based materials is the delivery of reliable components of controlled durability with minimum maintenance needs and life cycle costs. New products, processes and construction rules require validation tools that could ensure their reliability and future development. In addition, European regulations have, over the years, imposed a number of directives and regulations to member states that are required to be implemented by both industry and member states. In this challenging context, CEN/TC 38 is the main source of methods for assessing the characteristics of new products, and as such, it plays an important role in providing manufacturers with adequate qualification methods for their products, thus helping them to meet the requirements of European regulations such as the Construction Products Regulation (CPR) and the BPR, which have a major impact on the wood industry and compel us to assess the performance of wood-based products and wood preservatives as well as the risk management and waste valorisation in the wood protection sector.

10.2.1 Overview of the existing regulations

The following are some of the major existing regulations that have impacted the assessment of wood durability:

- Regulation (EC) No. 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (*EEC*) No. 793/93 and Commission Regulation (EC) No. 1488/94 and Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC.

- The consolidated version of Regulation (EC) No. 1272/2008 on the classification, labelling and packaging of substances and mixtures (*CLP*).
- Directive 89/106/EEC on the approximation of laws, regulations and administrative provisions of the member states relating to construction products.
- Commission Directive 2003/2/EC of 6 January 2003 relating to restrictions on the marketing and use of arsenic (tenth adaptation to technical progress to Council Directive 76/769/EEC).
- Biocidal Products Directive (*BPD*) 98/8/EC concerning the placing of biocidal products on the market. The BPD aims to harmonise the European market for biocidal products and their active substances. At the same time, it aims to provide a high level of protection for humans, animals and the environment.
- BPR (Regulation (EU) 528/2012) concerning the placing on the market and use of biocidal products, which are used to protect humans, animals, materials or articles against harmful organisms like pests or bacteria, by the action of the active substances contained in the biocidal product.
- Construction Products Directive (EU) No. 89/106/EEC (CPD), whose six essential requirements that should be fulfilled by construction products during a 'reasonable service life' reflect the importance of service life issues.
- Construction Products Regulation (EU) No. 305/2011 (CPR), adopted on 9 March 2011, repealed the CPD. It introduced a seventh essential requirement concerning sustainable use of natural resources and laid down conditions for the placing or making available on the market of construction products by establishing harmonised rules (*hEN*) of expressing the performance of construction products in relation to their essential characteristics and using CE marking on those products.

10.2.2 Focus on the construction products regulation

According to the Construction Products Regulation (CPR, EU No. 305/2011), after 1 Jul. 2013, only CE-marked construction products for which harmonised European standards (hENs) exist can be placed on the European market. All temporary or non-regulated work is exempt from the CPR, typical exemption examples being furniture, exhibitions, concrete formwork or portable buildings. Requirements vary between the various EU member states and are often related directly to national regulations. The responsibility for ensuring that a product has the correct characteristics for a particular application rests with the designers, contractors and local building authorities.

The CPR aims to prevent technical barriers to trade and requires in this context declaration of certain properties. Therefore, in order to meet the third of the essential requirements, 'hygiene, health and the environment', manufacturers must declare the content or emission of some substances defined as 'regulated dangerous substances' in the CE marking of construction products. However, it is important to note that CE marking does not mean that a product is safe per itself, as no risk assessment has to be performed in this context.

The construction products that are the subject of the CPR with respect to CE marking have been defined by the EC, and mandates have been issued to CEN for the work of the products TCs. These mandates are currently being amended by DG Enterprise and communicated through the Central Management of CEN/CENELEC in order to define the work and the scope of the products TCs. The amended mandates will result from a detailed review of the different national regulations on dangerous substances for each construction product. The answers to the mandates are drafted by products TCs and submitted

for approval to the EC through the Expert Group on Dangerous Substances (*EGDS*). These address the question which substances shall be dealt with and which test method shall be used. The work programmes proposed by each product TC will only deal with issues which have not yet been covered elsewhere, for example, some other legislation.

CEN/TC 351 was established in 2007 following the publication of CPD (89/106/EEC) with the mission of working out methodologies and horizontal test methods under mandate M/366 to avoid barriers to trade. These test methods can be drawn upon by product TCs and used in the development of product standards and CE marking.

10.2.3 Focus on the biocidal products regulation

A biocidal product is a substance intended to destroy, deter, render harmless and prevent the action of or exert a controlling effect on any harmful organism by any means other than mere physical or mechanical action. Biocidal products and active substances are all regulated by the EU under the BPR (Regulation (EU) 528/2012), which aims to harmonise the European market for biocidal products, their active substances and the treated articles and to ensure a high level of protection for humans and the environment. The text was adopted on 22 May 2012 and the regulation became operative on 1 Sep. 2013, with a transitional period for certain provisions. It repealed the BPD (Directive 98/8/EC).

The regulated substances have to be authorised before being used or sold on the EU market, and all treated products shall only contain authorised active substances. To receive the required authorisation, manufacturers need to submit technical documentation on the products concerned, including the results of biological efficacy tests. The aim of biocides used in the field of wood preservation is to prevent microbial damage or decay, which is detrimental to the functionality of an item or material. Biocides can act in different ways against microorganisms, and so, the purpose of using a particular biocide should be clear. This means that a biocidal active substance is required to show efficacy against the type of organisms it claims to be active against.

The efficacy documentation needed is described in Technical Notes for Guidance (TNsG). For wood preservatives (Product-type 8), the corresponding TNsG 'TNsG for Product-type 8 (wood preservatives)' (ECHA, 2015) mostly follows the guidelines of the standards EN 599-1 (CEN (2013b)) (preventive efficacy) and EN 14128 (CEN (2003b)) (curative efficacy).

The approval of active substances takes place at Union level and the subsequent authorisation of the biocidal products at the member state level. This authorisation can be extended to other member states by mutual recognition.

10.2.4 European legislation and mandates for bio-based products

The bio-based product market has been identified as a lead market by the European Commission's Lead Market Initiative. The Lead Market Initiative has aimed to support the uptake of a series of specific sectors by using policy instruments such as regulation, public procurements, standardisation and other supporting activities, in order to lower barriers and thus help bring these new products into the market. Standards are seen as essential elements in aggregating initial demand, in particular for new

bio-based products. Standards for bio-based products can help increase market transparency by providing common reference methods and requirements in order to verify claims about these products (e.g. biodegradability, bio-based content, recyclability and sustainability). The importance of standards is also highlighted by the European Commission Communication COM (2012a) 60 on a Bioeconomy for Europe and in the Commission Communication COM (2012b) 582 on A Stronger European Industry for Growth and Economy Recovery, which identifies bio-based products as one of the priority lines in which to focus investments and innovation.

Within the framework of the Lead Market Initiative for bio-based products, the European Commission has identified the need for European standards for these products, particularly for the determination of bio-based content and other product capabilities including functionalities, the evaluation of environmental impact and a number of other purposes. To address the absence of such standards, the Commission has issued several standardisation mandates to CEN (M/430 on biopolymers and bio-lubricants, M/491 on bio-solvents and bio-surfactants and M/492 for the development of horizontal standards for bio-based products). CEN is currently developing standards under the following mandates in the area of bio-based products:

> *Producing sustainable bio-based materials is challenging and makes it crucial to work out reliable standards that take consideration of both the expectations of end-users and the broad set of parameters that may influence performance and service life, such as exposure to moisture, climatic variations, and design.*

References

ASTM, 2008. ASTM C1338: 2008. Standard Test Method for Determining Fungi Resistance of Insulation Materials and Facings. ASTM International, West Conshohocken, PA. www.astm.org.

Botton, B., Breton, A., Fevre, M., Gauthier, S., Guy, P.-H., Larpent, J.-P., Reymond, P., Sanglier, J.-J., Vayssier, Y., Veau, P., 1990. Moisissures utiles et nuisibles. Importance industrielle, second ed. Masson, Paris. P312-313, 512 p.

BS, 1989. BS 3900-G6: 1989. Methods of Test for Paints—Part G6: Assessment of Resistance to Fungal Growth. BSI (British Standards Institute), London.

CEN, 1994a. EN 350-1:1994. Durability of Wood and Wood-Based Products—Natural Durability of Solid Wood—Part 1: Guide to the Principles of Testing and Classification of the Natural Durability of Wood. European Committee for Standardization, Brussels, Belgium.

CEN, 1994b. EN 350-2:1994. Durability of Wood and Wood-Based Products—Natural Durability of Solid Wood—Part 2: Guide to Natural Durability and Treatability of Selected Wood Species of Importance in Europe. European Committee for Standardization, Brussels, Belgium.

CEN, 2003a. EN 14119:2003. Testing of Textiles—Evaluation of the Action of Microfungi. European Committee for Standardization, Brussels, Belgium.

CEN, 2003b. EN 14128:2003. Durability of Wood and Wood-Based Products. Performance Criteria for Products for Curative Uses Against Wood Attacking Organisms as Determined by Biological Tests. European Committee for Standardization, Brussels, Belgium.

CEN, 2006. EN 927-5:2006. Paints and Varnishes. Coating Materials and Coating Systems for Exterior Wood. Assessment of the Liquid Water Permeability. European Committee for Standardization, Brussels, Belgium.

CEN, 2007. CEN/TS 1099:2007. Plywood—Biological Durability—Guidance for the Assessment of Plywood for Use in Different Use Classes. European Committee for Standardization, Brussels, Belgium.

CEN, 2012. EN 152:2012. Wood Preservatives. Determination of the Protective Effectiveness of a Preservative Treatment Against Blue Stain in Wood in Service. Laboratory Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2013a. EN 335:2013. Durability of Wood and Wood-Based Products—Use Classes: Definitions, Application to Solid Wood and Wood-Based Products. European Committee for Standardization, Brussels, Belgium.

CEN, 2013b. EN 599-1:2009+A1:2013. Durability of Wood and Wood-Based Products. Efficacy of Preventive Wood Preservatives as Determined by Biological Tests. Specification According to Use Class. European Committee for Standardization, Brussels, Belgium.

CEN, 2014a. CEN/TS 16640:2014. Bio-Based Products—Determination of the Bio-Based Carbon Content of Products Using the Radiocarbon Method) for the Bio-Based Carbon Content Determination. European Committee for Standardization, Brussels, Belgium.

CEN, 2014b. EN 15101-1:2014. Thermal Insulation Products for Buildings—In-Situ Formed Loose Fill Cellulose (LFCI) Products—Part 1: Specification for the Products Before Installation. European Committee for Standardization, Brussels, Belgium.

CEN, 2014c. EN 15534-1:2014. Composites Made From Cellulose-Based Materials and Thermoplastics (Usually Called Wood–Polymer Composites (WPC) or Natural Fibre Composites (NFC))—Part 1: Test Methods for Characterization of Compounds and Products. European Committee for Standardization, Brussels, Belgium.

CEN, 2014d. EN 16575:2014. Bio-based Products—Vocabulary. European Committee for Standardization, Brussels, Belgium.

CEN, 2014e. EN 252:2014. Durability of Wood and Wood-Based Products. Field Test Method for Determining the Relative Protective Effectiveness of a Wood Preservative in Ground Contact. European Committee for Standardization, Brussels, Belgium.

CEN, 2014f. CEN/TR 16721:2014. Bio-Based Products—Overview of Methods to Determine the Bio-Based Content. European Committee for Standardization, Brussels, Belgium.

CEN, 2015a. EN 16785-1:2015. Bio-Based Products—Bio-Based Content - Part 1: Determination of the Bio-Based Content Using the Radiocarbon Analysis and Elemental Analysis. European Committee for Standardization, Brussels, Belgium.

CEN, 2015b. EN 16760:2015. Bio-Based Products—Life Cycle Assessment. European Committee for Standardization, Brussels, Belgium.

CEN, 2016a. prEN 16785-2:2016. Bio-Based Products—Bio-Based Content—Part 2: Determination of the Bio-Based Content Using the Material Balance Method. European Committee for Standardization, Brussels, Belgium.

CEN, 2016b. EN 350:2016. Durability of Wood and Wood-Based Products—Testing and Classification of the Durability to Biological Agents of Wood and Wood-Based Materials. European Committee for Standardization, Brussels, Belgium.

CEN, 2016c. prEN 17009:2016. Flooring of Lignified Materials Other than Wood—Characteristics, Evaluation of Conformity and Marking. European Committee for Standardization, Brussels, Belgium.

CEN, 2016d. EN 16751:2016. Bio-Based Products—Sustainability Criteria. European Committee for Standardization, Brussels, Belgium.

CEN, 2016e. prEN 16818:2016. Durability of Wood and Wood-Based Products—Moisture Dynamics of Wood and Wood-Based Products. European Committee for Standardization, Brussels, Belgium.

CUAP (Common Understanding of Assessment Procedure), 2009. European Organisation for Technical Assessment. Belgium, June 2003, Rev. October 2009.

ECHA, 2015. Transitional Guidance on the Biocidal Products Regulation—Transitional Guidance on Efficacy Assessment for Product Type 8 Wood Preservatives. ECHA (European Chemicals Agency), Helsinki, Finland.

European Commission, 2007. Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and The Committee of the Regions. A lead market initiative for Europe COM (2007) 860. European Commission, Brussels, Belgium.

European Commission, 2012a. Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and The Committee of the Regions. Innovating for Sustainable Growth: A Bioeconomy for Europe COM (2012) 60. European Commission, Brussels, Belgium.

European Commission, 2012b. Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and The Committee of the Regions. A Stronger European Industry for Growth and Economic Recovery Industrial Policy Communication Update COM (2012) 582. European Commission, Brussels, Belgium.

Flannigan, B., Morey, P., Broadbent, C., Brown, S.K., et al., 1996. ISIAQ Guideline, Taskforce I: Control of Moisture Problems Affecting Biological Indoor Air Quality. International Society of Indoor Air Quality and Climate, Espoo.

Hill, C.A., 2007. Wood Modification: Chemical, Thermal and Other Processes. John Wiley & Sons, Hoboken, NJ.

ISO, 1977a. ISO 3998:1977. Textiles—Determination of Resistance to Certain Insect Pests is Applicable to All Textiles Containing Animal Fibres in Any Proportion. International Organization for Standardization, Geneva, Switzerland.

ISO, 1997b. ISO 846:1997. Plastics. Evaluation of the Action of Microorganisms. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006. ISO 15686-7:2006. Buildings and Constructed Assets—Service Life Planning—Part 7: Performance Evaluation for Feedback of Service Life Data From Practice. International Organization for Standardization, Geneva, Switzerland.

ISO, 2008. ISO 15686-8:2008. Buildings and Constructed Assets—Service-Life Planning—Part 8: Reference Service Life and Service-Life Estimation. International Organization for Standardization, Geneva, Switzerland.

ISO, 2012. ISO 15686-2:2012. Buildings and Constructed Assets—Service Life Planning—Part 2: Service Life Prediction Procedures. International Organization for Standardization, Geneva, Switzerland.

ISO, 2014a. ISO 15686-4:2014. Building Construction—Service Life Planning—Part 4: Service Life Planning Using Building Information Modelling. International Organization for Standardization, Geneva, Switzerland.

ISO, 2014b. ISO 535:2014. Paper and Board—Determination of Water Absorptiveness—Cobb Method. International Organization for Standardization, Geneva, Switzerland.

Jones, D., 2012. Life since the European thematic network on wood modification: the first 10 years. In: Hill, C.A.S., Militz, H., Pohleven, F. (Eds.), Proceedings of the 6th European Conference on Wood Modification. University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology, Ljubljana. 17–18 September.

Kutnik, M., Suttie, E., Brischke, C., 2014. European standards on durability and performance of wood and wood-based products—trends and challenges. Wood Mater. Sci. Eng. 9 (3), 122–133.

Meyer, L., Brischke, C., Preston, A.F., 2014. Testing the natural durability of timber exposed above ground—a review on methodology. Wood Mater. Sci. Eng. 11 (5) 282–304. http://dx.doi.org/10.1080/17480272.2014.983163.

Meyer-Veltrup, L., Brischke, C., Källander, B., 2016. Comparative study on durability and moisture performance of wood using 27 different test methods. Eur. J. Wood Wood Prod. http://dx.doi.org/10.1007/s00107-016-1137-8.

NF, 1992. NF X 41-547: 1992. Wood Preservatives—Determination of Fungicide Efficacy of Temporary Wood Protectives for Green Sawn Timber—Laboratory Method. AFNOR (Agence Française de Normalisation), Saint-Denis, France.

Glossary

A

Acetylation The process (in bio-based materials) where a hydroxy group is chemically reacted to form an acetyl ester group. The most common method for doing this is by reacting with acetic anhydride.

Adsorption The adhesion of atoms, ions or molecules from a gas, liquid or dissolved solid to a surface, related to the surface energy of the material and adsorbates.

Aerenchyma A spongy tissue that forms spaces or air channels in the leaves, stems and roots of some plants, which allows exchange of gases between the shoot and the root.

Ageing The gradual process in which the properties of a material, structure or system change (for better or worse) over time or with use, due to biological, chemical or physical agents. Corrosion and weathering are examples of ageing.

Alkyd A modified polyester prepared by the addition of fatty acids, diacids or acid anhydrides and other components, such as polyols.

Anisotropy A term for selected properties of a material that are directionally dependent within a three-dimensional matrix, which results in different properties in different directions.

Anobiidae A family of beetles, known for larvae to burrow into wood and furniture. An example of this family is *Anobium punctatum* (common furniture beetle).

Ascomycete A subdivision of fungi in which the spores are produced in sacs (asci), these spores being released considerable distances upon bursting of the sacs.

B

Basidiomycete A subdivision of fungi in which spores grow at the end of a microscopic cell (basidia).

Bethell process Also known as full-cell process, involves sealing the wood in a pressure chamber and applying a vacuum in order to remove air and moisture from the wood cells. The wood is then pressure-treated with preservatives in order to impregnate the full wood cell (i.e. the cell wall and the lumen or interior) with substances that impart resistance to decay, fire, insects and wood-boring marine animals.

Biocide An active substance and preparation containing one or more active substances, put up in the form in which they are supplied to the user, intended to destroy, deter, render harmless, prevent the action of or otherwise exert a controlling effect on any harmful organism by chemical or biological means.

Biocidal Products Directive (BPD) Also known as the Biocides Directive, European Union Directive, officially known as Directive 98/8/EC of the European Parliament, which became legislation on 16 Feb. 1998, concerning the placing of biocidal products on the market.

Biocidal Product Regulation (BPR) European Union Directive (Regulation (*EU*) 528/2012) that replaced the Biocidal Products Directive (98/8/EC). It concerns the placing on the market and use of biocidal products, which are used to protect humans, animals,

materials or articles against harmful organisms, like pests or bacteria, by the action of the active substances contained in the biocidal product.

Blue stain (sap stain) Stain caused by fungi in which the discoloration ranges from pale blue to black (as defined in EN 1001-2).

Bottom-up approach The piecing together of systems to give rise to more complex systems, thus making the original systems subsystems of the emergent system. Bottom-up processing is a type of information processing based on incoming data from the environment to form a perception.

BREEAM Building Research Establishment Environmental Assessment Method, first published by the Building Research Establishment (*BRE*) in the United Kingdom in 1990, is the world's longest established method of assessing, rating and certifying the sustainability of buildings.

Brown-rot fungi A fungal species that typically breaks down the hemicellulose and the cellulose. Some examples of species in this category are *Serpula lacrymans*, *Fibroporia vaillantii* and *Coniophora puteana*, which may attack timber in buildings.

C

Carbon capture (sequestration) The long-term storage of atmospheric carbon dioxide to mitigate or defer global warming through biological, chemical and physical processes.

CCA Chromated copper arsenate was developed as a wood preservative in the 1930s, combining the fixative properties of chromium with antifungal activity of copper and insecticidal properties of arsenic. Due to health implications, it has been widely replaced by newer treatments such as alkaline copper quaternary (*ACQ*) compounds and copper azole (CuAz).

CCB Chromated copper borate was developed as an alternative preservative to CCA, due to arsenic toxicity and was intensively used in several European countries.

Cerambycidae A widely dispersed family of beetles, typically characterised by extremely long antennae, which are often as long as or longer than the beetle's body. Often better known as longhorn beetles.

CIE L*a*b It is a colour space specified by the International Commission on Illumination (French, internationale de l'éclairage). It describes all the colours visible to the human eye and was created to serve as a device-independent model to be used as a reference, where L* refers to lightness, a* to the position between red and green and b* the position between yellow and blue.

Coleoptera The largest family of insects, often referred to as beetles. Typified by their front pair of wings being hardened into wing cases (known as elytra).

Construction Products Regulation (CPR) Regulation No. 305/2011 of 9 Mar. 2011 of the European Parliament and of the European Council that lies down harmonised conditions for the marketing of construction products and replaces Construction Products Directive (89/106/EEC). The EU regulation is designed to simplify and clarify the existing framework for the placing on the market of construction products.

COST Set up in 1971, Cooperation in Science and Technology (*COST*) aims to close the gap between science, policy makers and society throughout Europe and beyond. It anticipates and complements the activities of the EU Framework Programmes, constituting a ‘bridge’ towards the scientific communities of COST Inclusiveness Target Countries. It also increases the mobility of researchers across Europe and fosters the establishment of scientific excellence.

Cross laminated timber (CLT) A wood-based panel system made from solid pieces of timber, where layers of boards are orientated perpendicular to adjacent layers and glued on the wide faces of each board, usually in a symmetric way so that the outer layers have the same orientation.

Code for Sustainable Homes It was the predecessor to the Home Quality Mark in the United Kingdom. Running from 2006 to 2015, it succeeded EcoHomes and was an environmental assessment method for rating and certifying the performance of new homes.

CPD (Construction Products Directive) It was the European Union Directive (Council Directive 89/106/EEC), now repealed, that aimed to remove technical barriers to trade in construction products between Member States in the European Union. This has now been replaced with Regulation (EU) No 305/2011, to simplify and clarify the existing framework and improve the transparency and the effectiveness of the existing measures.

Creosote It is a category of carbonaceous chemicals formed by the distillation of various tars and by pyrolysis of plant-derived material, such as wood or fossil fuel. They are typically used for impregnation of railway slippers.

D

Desorption Opposite of adsorption; phenomenon whereby atoms, ions or molecules from a gas, liquid or dissolved solid are released from or through a surface. This occurs in a system being in the state of sorption equilibrium between bulk phase (fluid, i.e. gas or liquid solution) and an adsorbing surface (solid or boundary separating two fluids).

Decay Decomposition (of organic matter) through the action of biodegradative organisms (e.g. bacteria, fungi or insects).

Deuteromycetes Also known as 'fungi imperfecti' because they do not fit into the commonly established taxonomic classifications of fungi based on biological species concepts or morphological characteristics of sexual structures. Usually, they are known to produce spores asexually (sporogenesis).

DGNB The abbreviation for Deutsche Gesellschaft für nachhaltiges Bauen e.V. (German Sustainable Building Council), is a building certification scheme that provides an objective description and assessment of the sustainability of buildings and urban districts. It can be tailored to a range of buildings and is based on fulfilling up to 50 sustainability criteria in areas such as ecology, economy, sociocultural aspects, technology, process workflows and site. Awards are given on a gold-silver-bronze categorisation.

Dicotyledones Also known as dicots – were one of the two groups into which all the flowering plants or angiosperms were formerly divided. The name refers to one of the typical characteristics of the group, namely, that the seed has two embryonic leaves or cotyledons. Among the around 200,000 species are most flowering plants and broad-leaved trees.

Dimensional stability Due to the hygroscopic nature of bio-based materials (particularly wood), they can absorb and desorb water and moisture. As they do so, this can cause the material to swell and shrink. This can cause performance problems such as warping, checking and splitting. Ideally, a material should not alter greatly during service and as such would be classed as dimensionally stable.

Discolouring fungi Microfungi deriving their nourishment from wood cell contents. Their growth results in discolouration of wood but does not cause significant decomposition (adapted from EN 1001-2).

Durability classes Classification of the biological durability of wood and wood-based materials against biological wood-destroying agents (decay fungi, subterranean termites, xylophagous insects and marine borers), based on the standard EN 350 (2016).

E

Earlywood The part of the wood in a growth ring of a tree that is produced earlier in the growing season. The cells of early wood are larger and have thinner walls than those produced later in the growing season.

Earth Overshoot Day Formerly known as Ecological Debt Day, it represents the day when the total renewable resources of the planet are used in a given year.

Embodied energy The sum of all the energy required to produce any goods or services, considered as if that energy was incorporated or 'embodied' in the product itself and in its entire service life and ultimately life cycle.

EMC (equilibrium moisture content) The moisture content at which the wood is neither gaining nor losing moisture; this however, is a dynamic equilibrium and changes with relative humidity and temperature.

Energy Star An international standard for energy-efficient consumer products and buildings originated in 1992 by the Environmental Protection Agency and the Department of Energy in the United States that has since been adopted by Australia, Canada, Japan, New Zealand, Taiwan and the European Union.

ETAG or European Technical Assessment Guidelines, relate to guidelines set out by the European Organisation for Technical Assessment (*EOTA*) in relation to documents providing information on the performance of a construction product, to be declared in relation to its essential characteristics. This definition is within the new Construction Products Regulation (EU/305/2011) of 2013 for all European member states and in the European Economic Area. Compliance allows a product to be awarded a CE mark.

Eudicotyledons Also referred to as eudicots, a monophyletic clade of flowering plants that had been called tricolpates or nonmagnoliid dicots. Numerous familiar plants are eudicots, including many common food plants, trees and ornamental plants.

Eurocodes The 10 European standards (EN; harmonised technical rules) specifying how structural design should be conducted within the European Union (EU). These were developed by the European Committee for Standardisation upon the request of the European Commission, which will provide a means to prove compliance with the requirements for mechanical strength and stability and safety in case of fire established by European Union law, a basis for construction and engineering contract specifications and a framework for creating harmonised technical specifications for building products (CE mark).

European Conference on Wood Modification (ECWM) Originally the final outcome from the European Thematic Network for Wood Modification within the European Fifth Framework research programme. ECWM has since 2003 become the main international conference dealing with all aspects of wood modification.

F

Fibre saturation point The term used in wood mechanics and especially wood drying to denote the point in the drying process at which only water bound in the cell walls remains – all other water, called free water, having been removed from the cell cavities.

Formaldehyde A naturally occurring organic compound with the formula CH_2O (H–CHO). It is the simplest of the aldehydes (R–CHO) and is also known by its systematic name methanal. The common name of this substance comes from its similarity and relation to formic acid. Formaldehyde is an important precursor to many other materials and chemical

compounds. It is mainly used in the production of industrial resins, e.g. for particle board and coatings. In view of its widespread use, toxicity and volatility, formaldehyde poses a significant danger to human health. In 2011, the US National Toxicology Program described formaldehyde as 'known to be a human carcinogen'.

Furfurylation A modification method involving the impregnation and polymerisation of a furfuryl alcohol mixture.

G

Glulam (glue-laminated timber) A type of structural engineered wood product comprising a number of layers of dimensioned lumber bonded together in the same orientation with durable, moisture-resistant structural adhesives.

Green Star A voluntary sustainability rating system for buildings in Australia. It was launched in 2003 by the Green Building Council of Australia based on evaluations according to management, indoor environment quality, energy, transport, water, materials, land use and ecology, emissions and innovation. The level of certification is based on the number of stars awarded (1–6).

H

HALS (hindered amine light stabilisers) Derivatives of 2,2,6,6-tetramethyl piperidine that are extremely efficient stabilisers against light-induced degradation of most polymers. They do not absorb UV radiation, but act to inhibit degradation of the polymer. They slow down the photochemically initiated degradation reactions, to some extent in a similar way to antioxidants.

Hardwood The wood from dicot angiosperm trees (such as oak, ash or beech – commonly referred to as broad-leaved trees) as distinguished from that of conifers.

HDF (high-density fibreboard) An engineered wood product that is similar to particle board and medium-density fibreboard (*MDF*) but is denser and much stronger and harder.

HQE (Haute Qualité Environnementale, High Quality Environmental standard) A standard for green building in France, based on the principles of sustainable development first set out at the 1992 Earth Summit. The standard is controlled by the Paris-based Association pour la Haute Qualité Environnementale (ASSOHQE). It specifies criteria for managing impacts on the outdoor environment and creating a pleasant indoor environment.

Hydrophobisation The act or process of making something hydrophobic or more water-repellent. Often, this can be achieved through a chemical treatment of a material.

Hygroscopicity The ability of a material to attract and absorb moisture from its surrounding atmospheric environment.

I

International Research Group on Wood Protection (formerly, International Research Group on Wood Preservation) IRG-WP An international network of researchers and industry concerned with the protection of wood and other bio-based products in service. Its major activity is an annual conference.

Ionic liquid A salt in the liquid state. In some contexts, the term has been restricted to salts whose melting point is below some arbitrary temperature, such as 100°C (212°F). Increasingly popular solvents for a range of processes, following the discovery that cellulose could be dissolved by an ionic liquid, namely, 1-alkylpyridinium chlorides.

Their use allows solvation of compounds at lower temperatures, allowing for complex chemical processing without the risk of thermal degradation.

IPBC A chemical (full name iodopropynyl butylcarbamate) that is a water-soluble preservative used globally in the productions of paints and coatings and wood preservatives and in the personal care and cosmetics industries.

IPCC (Intergovernmental Panel on Climate Change) A scientific and intergovernmental body under the auspices of the United Nations, set up in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) and later endorsed by the United Nations General Assembly through Resolution 43/53, to provide the world with an objective, scientific view of climate change and its political and economic impacts.

Isoptera Species of insects more commonly known as termites, of which more than 3000 species are known. Although these insects are often called white ants, they are not ants.

K

Kyoto Protocol An international treaty that extends the 1992 United Nations Framework Convention on Climate Change (UNFCCC) that commits state parties to reduce greenhouse gas emissions, based on the premise that (a) global warming exists and (b) human-made CO_2 emissions have caused it. The Kyoto Protocol was adopted in Kyoto, Japan, on 11 Dec. 1997 and entered into force on 16 Feb. 2005.

L

Latewood The part of the wood in a growth ring of a tree that is produced later in the growing season. The cells of late wood are smaller and have thicker cell walls than those produced earlier in the season.

LCA (life-cycle analysis) A technique to assess environmental impacts associated with all the stages of a product's life from raw-material extraction through material processing, manufacture, distribution, use, repair and maintenance and disposal or recycling.

LCC (life-cycle cost) The outcome from a life-cycle cost analysis (*LCCA*) to determine the most cost-effective option among different competing alternatives to purchase, own, operate, maintain and, finally, dispose of an object or process, when each is equally appropriate to be implemented on technical grounds.

LEED (Leadership in Energy and Environmental Design) It is one of the most popular green building certification programs used worldwide. Developed by the US Green Building Council (USGBC), it includes a set of rating systems for the design, construction, operation and maintenance of green buildings, homes and neighbourhoods that aims to help building owners and operators be environmentally responsible and use resources efficiently.

Lignocellulose Typically plant dry matter (biomass), it is the most abundantly available raw material on the Earth for the production of biofuels, mainly bioethanol. It is composed of carbohydrate polymers (cellulose and hemicellulose) and an aromatic polymer (lignin).

Limnoriidae Any of about 56 species of marine isopod commonly known as gribble. They are wood-boring crustaceans that are mostly pale white and small (typically 1–4 mm or 0.04–0.16 in. long).

LSL (laminated strand lumber) A form of engineered wood product. They are manufactured from flaked wood strands that have a high length-to-thickness ratio. Combined with an adhesive, the strands are oriented and formed into a large mat or billet and pressed.

LVL (laminated veneer lumber) A type of structural composite lumber. LVL is produced by bonding thin wood veneers together with the grain in the same direction in a large billet. The resulting product features enhanced mechanical properties and dimensional stability that offer a broader range in product width, depth and length than conventional lumber.

Lyctidae A seldom-used term for lyctinae.

Lyctinae A species of around 70 beetles more commonly known as the powderpost beetle.

M

Maintenance The process of preserving a condition or situation or the state of being preserved. For building materials, the processes necessary to ensure product performance and aesthetics are maintained.

Material climate Moisture and temperature conditions within a building material or component.

MDF (medium-density fibreboard) A form of engineered wood (or bio-based fibre) product manufactured from fibres and resin blends, typically pressed to densities between 500 and 750 $kg\,m^{-3}$.

MOE Modulus of elasticity, also known as the elastic modulus, the tensile modulus or Young's modulus, is a number that measures an object or substance's resistance to being deformed elastically (i.e. nonpermanently) when a force is applied to it.

Moisture content Quantity of water contained in a material expressed as a ratio, which can range from 0 (completely dry) to the value of the materials' porosity at saturation. Usually referring to the oven-dry weight of the material.

Monocotyledones Commonly referred to as monocots, are flowering plants (angiosperms) whose seeds typically contain only one embryonic leaf or cotyledon. The monocots include about 60,000 species, such as bamboo, palms, wheat, rice, rattan and miscanthus.

MOR Modulus of rupture, also known as flexural strength or bend strength or transverse rupture strength, is a material property defined as the stress in a material just before it yields in a flexure test.

Mould fungi Fungal growth having a woolly or powdery appearance that can form on the surface of wood in damp conditions (as defined in EN 1001-2).

N

NABERS The National Australian Built Environment Rating System is an initiative by the government of Australia to measure and compare the environmental performance of Australian buildings and tenancies. There are NABERS rating tools for commercial office buildings to measure greenhouse gas emissions, energy efficiency, water efficiency, waste efficiency and indoor environment quality.

Nonconjugated The opposite to conjugated, in that there are not alternating single and double bonds within a molecule that would result in a system of connected p orbitals with delocalised electrons.

O

Orthotropic A material that is one that has different material properties or strengths in different orthogonal directions.

OSB (oriented strand board) It is a type of engineered lumber formed by adding adhesives and then compressing layers of wood strands (flakes) in specific orientations. It was invented by Armin Elmendorf in California in 1963 and is often known as flakeboard, sterling board or aspenite.

P

Parenchyma Tissue of nonwoody structures. Parenchyma cells are living and have thin cell wall as compared with other cells.

Passive house (German, Passivhaus) It is a rigorous, voluntary standard for energy efficiency in a building, reducing its ecological footprint. It results in ultralow energy buildings that require little energy for space heating or cooling. A similar standard, MINERGIE-P, is used in Switzerland.

PCP An organochlorine compound, pentachlorophenol is used as a pesticide and a disinfectant. First produced in the 1930s, it is marketed under names such as Santophen, Pentachlorol, Chlorphen, Chlon, Dowicide 7, Pentacon, Penwar, Sinituho and Penta.

Penetration It is the depth to which preservative chemicals are forced into the wood. It is an indication of the amount of protection provided.

Performance Ability of a wood species or a material to withstand deterioration over time. Performance can depend on a number of factors, which will vary in importance depending on the end use (adapted from EN 350).

Performance-based building design Approach to the design of any complexity of building, from single-detached homes up to and including high-rise apartments and office buildings. A building constructed in this way is required to meet certain measurable or predictable performance requirements, such as energy efficiency or seismic load, without a specific prescribed method by which to attain those requirements.

Plasmodesmata Microscopic channels that traverse the cell walls of plant cells and some algal cells, enabling transport and communication between them.

PSL (parallel strand lumber) It is a form of engineered wood made from parallel wood strands bonded together with adhesive, where clipped veneer elements having a least dimension of not more than 0.25 in. (6.4 mm) and an average length of at least 300 times this least dimension. It is used for beams, headers, columns and posts, among other uses.

Q

Quaternary ammonium compounds Group of biocides also known as quats, are positively charged polyatomic ions of the structure NR_4^+, R being an alkyl group or an aryl group. They are widely used in the wood preservation alone or in combination with other active ingredients.

R

Relative humidity (RH) The ratio of the partial pressure of water vapour to the equilibrium vapour pressure of water at a given temperature. Relative humidity depends on temperature and the pressure of the system of interest.

Retting A process employing the action of either chemicals or microorganisms and moisture on plants to dissolve or rot away much of the cellular tissues and pectins surrounding bast fibre bundles and so facilitating separation of the fibre from the stem.

Retention It is usually expressed in kilograms of preservative per cubic metre of wood. This indicator represents the amount of preservative retained in the wood after completion of the treating cycle and is one of the most important measures of the degree of protection provided.

Rüping process A treatment for preserving wood with the use of a minimum amount of wood preservative by alternating pressure and vacuum so that only the walls of the wood cells are coated and the cells themselves are not filled.

S

SCL (structural composite lumber) A group of engineered wood products, of which laminated strand lumber (LSL) and orientated strand lumber are examples.

Service life A commitment made by the item's manufacturer and is usually specified as a median. It is the time that any manufactured item can be expected to be 'serviceable' or supported by its manufacturer.

Service classes Classes of service conditions (i.e. moisture content, temperature and relative humidity) according to Eurocode 5 (EN 1995-1-1: 2008) that timber structures shall be assigned to. The service class system is mainly aimed at assigning strength values and for calculating deformations under defined environmental conditions.

Soft-rot fungi A family of fungi that secretes cellulase from their hyphae, an enzyme that breaks down cellulose in the wood. This leads to the formation of microscopic cavities inside the wood and sometimes to a discolouration and cracking pattern similar to brown rot. Soft-rot fungi need fixed nitrogen in order to synthesise enzymes, which they obtain either from the wood or from the environment.

Softwood The wood from gymnosperm trees such as conifers.

Sol-gel A method for producing solid materials from small molecules, where there is a conversion of monomers into a colloidal solution (sol) that acts as the precursor for an integrated network (or gel) of either discrete particles or network polymers.

Strengths/weaknesses/opportunities/threats (SWOT) analysis A structured planning method that evaluates those four elements of an organization, project or business venture, involving specifying the objective of the business venture or project and identifying the internal and external factors that are favourable and unfavourable to achieve that objective.

Sustainability Property of biological systems to remain diverse and productive indefinitely. In more general terms, sustainability is the endurance of systems and processes.

T

Teredinidae A family of salt-water wood-destroying marine bivalve molluscs with long, soft, naked bodies, often called shipworms.

Termites Social insects classified in various families. Termites can attack wood, cellulose-based materials and generally any kind of building or other materials that are soft enough to allow their destruction, even if not used as a direct source of food (as defined in EN 335).

Terrestrial microcosm chamber (TMC) A laboratory-based exposure method comprising naturally occurring soils of known biodegradation activity that are used to determine levels of fungal decay under fixed predetermined conditions.

Thatching Craft of building a roof with dry vegetation such as straw, water reed, sedge, rushes, heather or palm fronds, layering the vegetation so as to shed water away from the inner roof.

Thermal conductivity (λ) The property of a material to conduct heat.

Thermal modification The process of heating wood and other bio-based materials at elevated temperatures (typically between 160°C and 240°C) in an inert condition (e.g. nitrogen, steam and in vacuo). Several commercial processes are currently marketed.

Time of wetness (ToW) Combination of water uptake and release of a material, taking into account time as a critical factor parameter and indicating how prone it is to fungal decay (adapted from EN 350).

Top-down approach (also known as stepwise design) is essentially the breaking down of a system to gain insight into its compositional subsystems in a reverse-engineering fashion. An overview of the system is formulated, specifying but not detailing any

first-level subsystems. Each subsystem is then refined in yet greater detail, sometimes in many additional subsystem levels, until the entire specification is reduced to base elements.

Triazoles Heterocyclic compounds with molecular formula $C_2H_3N_3$, having a five-membered ring of two carbon atoms and three nitrogen atoms. Predominantly, tebuconazole and propiconazole are used in wood preservation.

U

U-value (thermal transmittance) Describes how well a building element conducts heat or the rate of transfer of heat (in watts) through 1 m^2 of a structure divided by the difference in temperature across the structure. It is measured with SI units of W/(m^2K) and US units of BTU/(h°F ft^2).

Use class Defined within harmonised standard EN 335:2013 as the five main service condition classes where solid wood and wood-based components are required to achieve expected performance. These classes are the following: (1) situation in which the wood-based product is inside a construction, not exposed to the weather and wetting; (2) situation in which the wood-based product is under cover and not exposed to the weather (particularly rain and driven rain) but not persistent, wetting can occur; (3) situation in which the wood-based product is above ground and exposed to the weather (particularly rain); (4) situation in which the wood-based product is in direct contact with ground and/or fresh water; and (5) situation in which the wood-based product is permanently or regularly submerged (i.e. sea water and brackish water).

V

Viscoelasticity The property of a substance of exhibiting both elastic and viscous behaviour, the application of stress causing temporary deformation if the stress is quickly removed but permanent deformation if it is maintained.

Volatile organic chemical (VOC) Organic chemicals that have a high vapour pressure at ordinary room temperature. Their high vapour pressure results from a low boiling point, which causes large numbers of molecules to evaporate or sublimate from the liquid or solid form of the compound and enter the surrounding air.

W

Wax Esters of long-chain acids with long-chain alcohols and free long-chain acids. Due to similar properties, paraffin could be considered as wax as well.

Weathering The change in appearance or texture of a material (e.g. a bio-based building material) by long exposure to atmospheric conditions (e.g. wind, precipitation and sunshine).

Weight percent gain (WPG) The weight gained by a material as a percentage of its original weight. Often used in describing the level of treatment in wood modification methods such as acetylation.

White-rot fungi A group of fungi that can break down lignin and cellulose and commonly cause rotted wood to feel moist, soft, spongy or stringy and appear white or yellow.

Wood-based products (WBP) Any processed matrix containing and/or made of a specific percentage of wood (as in EN 350).

Wood modification The alteration of wood at the molecular level to achieve a desired property change. Wood modification can be split into two distinct groups. Active modification relies upon a chemical change induced by reactive chemistry, physical or biological means. Passive modification does not alter the chemical constituents of wood but changes the wood permanently by a treatment (such as impregnation-polymerisation processes).

Wood plastic (or polymer) composites (WPC) A blend of materials made of wood fibre/wood flour and thermoplastic(s) (includes *PE*, *PP* and *PVC*). WPCs are a subset of a larger category of materials called natural fibre plastic composites (*NFPCs*), which may contain no cellulose-based fibre fillers such as pulp fibres, peanut hulls, bamboo and straw.

This page intentionally left blank

Index

Note: Page numbers followed by *f* indicate figures and *t* indicate tables.

A

Absolute global warming potential (AGWP), 557
Accoya wood, 33
Acetylation, 214
Acoustic insulation, 136
Acoustic performance, 256, 256*f*
Acoustic protection, 256
Aesthetics
  bio-based material versatility, 286, 287*f*
  customer preferences, 292–293
  definition, 285
  functions, 286
  material perception, 286–288
  material selection, 293–294
  modelling, 285
  and service life, 288–291
Agar block test, 387
Air infiltration, 76
Air velocity, 358
Annual rings, 23
Anobium punctatum (furniture beetle), 195–196, 195–196*f*, 396–397
Archetypal stains, 222
Architects, air quality, 361
Assessment tools, 6, 8*t*

B

Bacterial decay, 392–393
Bamboo, 120*f*
  bahareque walls, 123
  charcoal, 124
  composites, 121, 122*f*
  creep behaviour, 124
  degradation, 123
  disadvantages, 120–121
  extraction, 123
  fibres, 121, 121*f*
  MDF, 123
  screen fence, crack formation, 282, 282*f*
  viscoelasticity, 123
  wood floorboard, 121, 122*f*
Bark, 78
  appearance, 78
  diversity, 79
  formation, 78–80
  functions, 78
Basidiomycetes, 259
Battenboard, 60
Beeswax, 226–227
Bio-based boards, 350*t*
Bio-based building materials
  acoustic protection, 256
  aesthetics, 251*f*, 252
  aesthetic versatility, 286
  benefits, 2
  dimensional and shape stability, 252–253
  embodied energy, 12–13
  end-grain erosion, 282, 283*f*
  human well-being, 256–257
  issues, 14–15
  moisture, 277–278
  role in modern building sector, 2–4
  slip resistance, 253–254
  stiffness and hardness, 253, 254*f*
  for structural purposes, 250
  sustainable agenda, 10–11
  sustainable planning, 11–12
  thermal insulation, 254–255
  uses, 4–9
Bio-based products
  resistance against biological agents, 603–604
  resistance against moulds, 602–603
Biocidal Product Regulation, 204
Biocides, 204–207, 205*t*
Biodegradability, 2
Bio-economy, 562–563
Biofilms, 253–254, 283
Biohygrothermal model, 487–488
Biopolymers, 63

Biotic decay, 289–290
Black alder wood waste, 63, 64*f*
Bleaching process, 71–72
Blockboard, 60
Blue-stain infestations, 221, 221*f*
Bottom-up approach, 12
BRE environmental assessment method (BREEAM), 6, 8, 577–578
Brown-rot fungi, 190, 190*f*
Building durability, 445
Building-level assessment methods, 573
Building occupants, 358
Building physics
  acoustic properties, 341–343
  bio-based materials, 345
  definition, 335
  hygrothermal properties, 337–341
  phase-change materials, 343–344
  properties, 336
Building regulations, 3–4, 5*t*

C

Canadian Wood Council (CWC), 50
Canal infrastructure, 44, 45*f*
Cancun agreement, 10–11
Capacitive measurement devices, 427*f*
Carbon accounting method
  AGWP, 557
  carbon storage benefits, 556–557
  carbon-trading scheme, 555–556
  GWP impact, 558–559
  harvested wood products, 555–556
  HWP pool, 559
  methodologies, 555–556
Carbon storage, 13
Cattails, 170
Cellulose, 24, 68–70
  accessibility, 74
  applications, 76–77
  degradation, 74–75
  dense packing installation, 77
  esterification, 75
  etherification, 75
  insulation, 75–76, 77*f*
  physical properties, 73–74
  structure, 69–70, 69*f*
  swellability, 73
Cell wall, 23
Cement boards, 60
Cerambycidae (longhorn beetles), 197
Chemical modification, 33
Chemical pulps, 71
Chemi-thermomechanical pulping (CTMP), 71
Chemomechanical pulping, 71
Circular economy, 560–562
Coating material, 218
Coating permeability, 220–222
Coleoptera (beetles), 193–194, 193–194*t*
Compounding process, 65
Compressed strawboard, 119
Computer numeric cutting (CNC) machine technology, 42–43
Construction market, 1
Construction Products Directive (CPD), 4–6
Cork, 78
  agglomerates, 84–85
  in construction, 83–86, 83*f*
  formation, 78–80
  granules, 84–85
  structure and properties, 80–82, 81–82*f*
Corn, 157–158, 160*f*
Corn cobs, 170, 172
Cortical cell, 129–130, 129*f*
Cradle-to-cradle (C2C) certification, 562
Cradle-to-gate assessment
  manufacturing
    common operation, 551–552
    modification treatments, 552
    production of bio-based boards, 552–553
  raw material supply
    additives, 550–551
    agriculture and animal products, 549–550
    forest products, 549
    recycled products, 551
  transportation, 551
Creosote, 206, 210*f*, 429–430
Cross laminated timber (CLT)
  evolution, 41
  fair-faced surface, 45, 46*f*
  game changers, 47–49
  lamellae, 40–41, 41*f*
  nailed stacked plank panel, 40
  properties and performance, 45–47
  tall timber buildings/vertical timber city, 50–51
  uses, 42–45

D

Decarbonised economy. *See* Low-carbon economy
Decay fungi
  classifications, 188, 189*t*
  fungal rot, 188–190
  physiological needs, 190–191, 191*t*
  temperature requirements, 190–191, 192*t*
Decay models
  biological models, 510
  black and white box model, 512
  challenges, 520–522
  climate indices, 512–513
  dose-response functions, 510–512, 511*f*
  hazard mapping, 516–517
  mathematical models, 510
  performance prediction, 513–516
  service life prediction and planning, 517–520
  variability, 521–522
Degree of exposure, 262
Developers, air quality, 361
DGNB system, 8–9
Dimensional stability, 252–253
1,3-Dimethylol-4,5-dihydroxy-ethyleneurea (DMDHEU), 216
Dipping method, 207
Doha agreement, 10–11
Do-it-yourself (DIY) products, 207
Dried block-peat, 148, 148*f*
Drilling resistance method, 458, 459*f*
Dry-wood insects, 194, 194*t*
Durability
  bamboo, 271
  biological decay and, 258–261
  classes, for fire retardants, 313–314
  definition, 257–258
  exterior out of ground contact conditions, 265–270
  in ground contact conditions, 265
  hazard/use classes, 261–262
  integrated approach, 262–263
  interior conditions, 270–271
  laboratory accelerated testing, 272–273
  lab test methods, 273–276
  nonwood products, 271
  statistical analysis, 276
  timber classes, 258, 258*t*
  wood products, 271

E

Earth overshoot day (EOD), 2–3, 3*t*
Eco-labels, 565–566
Economic issues, 14
80-storey Barbican Oak project, 51, 51*f*
ELODIE, 580
Embodied energy, 12–13
Empirical aesthetics, 286
Energy efficiency
  bio-based product evaluation, 347–349
  bioeconomy, 351
  definition, 345
  energy requirement reduction, 345–346
  smart bio-based materials, 346–347
Environmental assessment
  bio-economy, 562–563
  of buildings, 576–584
  carbon accounting, 554–559
  circular economy, 560–562
  construction stage, 553
  end of life stage, 554
  life cycle assessment, 548
  low-carbon economy, 564
  measurement and certification, 565–584
  product stage, 548–553
  use stage, 553
Environmental labels
  certifications, 572
  drivers, 572–576
  EPD in Europe, 569–572
  types, 565–569
Environmental product declarations (EPD)
  in Europe, 569–572, 575*t*
  for wood products, 573*f*
EOD. *See* Earth overshoot day (EOD)
Epicuticle, 130
Equilibrium moisture content (EMC), 408–409
Eurocodes, 4, 7*t*
European Chemical Agency (ECHA), 204–206
European classification system (EN 13501-1), 309–311
European Directives, 363, 363*t*
European regulations, wood-based products
  biocidal products regulation, 606
  Construction Products Regulation, 605–606
  existing regulations, 604–605
  Lead Market Initiative, 606–607

European standardisation
biological durability, 602–604
European regulations
biocidal products regulation, 606
Construction Products Regulation, 605–606
existing regulations, 604–605
Lead Market Initiative, 606–607
wood and wood-based products, 594–595
biological resistance, 596–597
moisture risk, 598–599
performance, 597–598
service life planning, 599–600
wood-disfiguring fungi, 599
European Technical Approval Guidelines (ETAGs), 4–6
Expanded polystyrene (EPS), 349
Exposure dosage, 265, 266*f*
quasi-continuous approach, 267–268, 267*f*
Extrusion process, 65

F

Factorisation, 238–239
Fibreboard, 52, 58–60, 59–60*t*
Fibre saturation point (FSP), 277–278, 407
Field testing, 385
description, 416
fungal decay, 416–418
termites, 421–422
weathering and leaching, 435–440
Film-forming coating, 220
Finite element analysis (FEA), 320
Fire performance
reaction to fire, 305–307
bio-based building products, 309
European system for, 309–311
wood products, 311–312
resistance to fire
bio-based building products, 315–317
load-bearing function, 317–320
separating function, 316–317
retardant treatments, wood products, 312–314
safety, 305
Fire resistance
mowing herbs, 153
peat, 146
of straw bale construction, 118, 119*f*
Fire safety engineering (FSE), 306
Fire testing, 320
Flame retardants, 67–68
Flax
application, 102–105
board, 99, 102–103
morphology, 100–102, 100–101*f*
production, 98–99
shives, 99, 102–103
stem, 98–99, 99*f*, 101*f*
Floating test method, 414–415
Flowerpot test, 421, 422*t*
Formaldehyde, 140, 141*f*, 353
Formaldehyde-based resins, 54, 63
Fourteen-storey treet building, 50, 50*f*
Fungal decay, 258–259
bio-based building materials, 280–281
field testing, 416–418
laboratory testing, 387–390
test methods, 388*t*
Furfurylation, 215–216

G

Glue lamination, 42
Grafting method, 227
Graphite, 362
Grass
in building structures, 154–155
hay bales, 151, 151*f*
mowing herbs, 153–154
thermal conductivity, 155, 156*t*
Graveyard test, 416, 416*f*
Green building, 21, 576–577
Greenhouse gas emissions, 12–13
Growth ring. *See* Annual rings

H

Hardboard (HB), 58–59
Hardness, 253, 254*f*
Hardwoods, 22, 23*f*
Harvested wood products (HWP), 555–556
Heartwood, 22–23
Heat flow (HF) method, 296, 297*f*
Heat release rate (HRR), 164, 165*f*
Hedonistic testing, 292, 293*f*
Hemicelluloses, 24–25, 25*f*, 32–33, 126
Hemp
applications, 110–112
bricks, 110
concrete, 110
mature plants, 106, 106*f*

morphology, 107–109, 108–109*f*
oil, 225
particle board, 110–111, 111*f*
production, 105–106
shiv, 107
stem, 106–107, 106*f*, 108*f*
uses, 106–107
Hempcretes, 111, 172
High Quality Environmental standard (HQE), 9
Hindered amine light stabilisers (HALS), 223
Hollow WPC profiles, 67, 67*f*
Horizon 2020 Framework programme, 346
Hot-plate (HP) method, 296, 296*f*
HQE-France, 579
HRR. *See* Heat release rate (HRR)
Human factors/ergonomics (HFE), 370
Human well-being
building materials, thermal properties of, 256–257
description, 365–366
design paradigms, 371
factors affecting, 366
future prospects, 372
human factors/ergonomics, 370
impact measurement, 371–372
material- and product-related factors, 368–369
material performance, 369–370
psychophysiological well-being, 367
Humic acid, 439
Humidity buffering, 338
Hydrolysis, 355–356
Hydrophobic treatment, 32
Hydrophobization agents, 225–227
Hydroxyl groups, 73
Hygroscopicity, 163
Hygro-thermal models, wood
future aspects, 502
moisture-induced stresses, 495
moisture-related degradation, 495–496
multi-Fickian method, 495–496, 498–500
recent advances, 495
single-Fickian model, 495–498
Hylotrupes bajulus (house longhorn beetle), 197, 197*f*, 397

I

IMPACT compliant tools, 580
Impregnation method, 208, 209–210*f*
Indoor air quality (IAQ)
air velocity, 358
architects and developers, 361
biological pollutants, 354–355
building occupants, 358
government and organisations, 363–365
hygric performance, 139–140, 139*f*
individual occupants, 360
manufacturers, 361–362
pollution, 351–353
primary pollutants, 353–354
relative humidity, 357
secondary pollutants, 355–356
temperature, 356
ventilation, 357
VOC abatement, 140–141
VOC sampling and analysis, 358–360
Injection moulding, 66, 66*f*
Insect monitoring, 454–456
In-service tests, 444
decay check, 457–458
description, 456
instrumented survey, 458–460
visual inspection, 456–457
Insulation corkboards (ICB), 343
Intergovernmental Panel on Climate Change (IPCC), 10–11
International Energy Agency (IEA), 10–11
Intrinsic durability, 258. *See also* Durability
Iodopropynyl butylcarbamate (IPBC), 204–206
Isoptera (termites), 198–199, 199*f*
subterranean, 199–200

K

Keratin, 129
Knowledge based bio-based products (KBBPS) project, 601
Konto-insulation plate, 148, 148*f*
Kraft sludge fibres, 64
Kyoto Protocol, 10–11

L

Laboratory testing, 385
Anobium punctatum (furniture beetle), 396–397
Anthrenus flavipes (carpet beetle), 397–398

Laboratory testing *(Continued)*
data interpretation and evaluation, 393–394
development, 394
digital image correlation, 411, 412*f*
durability, 273–276
fungal decay, 387–390
Hylotrupes bajulus (longhorn beetle), 397
limnoriids, 402–404
lyctid beetle borers, 396
marine borers, 400–402
teredinids, 404–405
termites, 394–396
Tineola bisselliella (clothes moth), 397–398
weathering and leaching, 430–435 (*see also* Weathering and leaching)
wood-based panel materials, 389–390
Laminboard, 60
Lap-joint test, 417, 417*f*
18 h lasting batch leaching tests, 433
Leaching protocols
Leadership in energy and environmental design (LEED), 6, 8
Least-square regression analysis, 116
LEED-United States, 578
Legal issues, 14
Legislation, 6
Lignin, 25, 126
Lignocellulosic materials, 161
Limnoria lignorum, 201, 201*f*
Limnoria quadripunctata, 399, 400*f*
Linseed oil, 225, 226*f*
L-joint test, 417, 417*f*
Load and resistance factor design (LRFD), 523, 525
Load-bearing structure, 250, 251*t*
Log buildings, 36, 36*f*
Longhorn beetles, 193–194
Low-carbon economy, 564
Low-density board, 167, 168*f*
Lumen, 101
Lyctidae (powder-post beetles), 198
Lyctidae brunneus (brown powder-post beetle), 198

M

Marine borers
field testing, 422–424
laboratory testing, 400–402
types, 398–400
Marino wool, 130, 131*t*
Martesia striata, 399–400
test method, 401–402
Material protection
biocides, 204–207, 205*t*
preservation techniques, 207–211, 207–210*f*
Mechanical performance modelling
background, 522–523
cracks, 530–532, 531*f*
degradation phenomena, 526–528, 527*t*
glued-laminated timber structure, 533–538, 533–534*f*
load and resistance factor design (LRFD) concept, 525–526
modelling approaches, 528–530, 529*f*
pile foundations, 532, 532–533*f*
reliability function, 523–526
Mechanical pulping, 71
Mediumboards, 60
Mercerisation, 74
Metal angle brackets, 44, 44*f*
Methylene diphenyl diisocyanate (MDI), 166–167
Microcrystalline cellulose, 76
Microfibril angle, 100–101
hemp, 108–109, 109*f*
Mini-block test, 387
Mini-stake test, 416–417, 416*f*
Modified transient plane source (MTPS) method, 297, 298*f*
Modulus of elasticity, 32
Modulus of rigidity (MOR), 32
Moisture, 188, 277–278
Moisture buffer capacities, 338, 339*f*
Moisture buffer value (MBV), 338
Moisture content (MC)
characteristic, 407
description, 406
discrimination of wood species, 415
EMC, 408–409
material moisture, 277
mechanical effects, wood matrix, 407–408
monitoring, 447–454
wood, 302–303
in wood, 406–407
Moisture ingress, bridge deck, 280, 281*f*

Moisture measurements
continuous, 267–268
field testing
capacitive method, 426–427
electrical resistance, 425–426
gravimetric methods, 425
hygroscopic method, 427
NMRI, 427–428
substitute sensors, 427
laboratory testing
electrical resistance, 410
gravimetric method, 409
neutron imaging, 411–413
NMRI, 413, 414*f*
X-ray computed tomography, 410–411
Moisture performance
bio-based building materials, 277–278
material properties, effects on, 281–284
moisture sources, 278–281
quantification measures, 284–285
Moisture protection, 229–230
Moisture storage function, 336
Monitoring, 444
design standards, 446–447
direct moisture measurement, 450–452
indirect moisture measurement, 448–450
insects, 454–456
MC assessment, 447–448
mechanical stresses, 452–454
Mould fungi, 192
Mould germination graph method, 487, 488*f*, 489*t*
Mould resistance design (MRD) model, 493–494, 494*t*
Moulds, 259
field testing, 418–419
laboratory testing, 391–392, 392*f*
test methods, 391*t*
Mowing herbs
chemical properties, 153
fire resistance, 153
mechanical properties, 154, 154–155*f*
mixtures of, 152, 153*f*
moisture conditions, 153
technological properties, 154
thermal properties, 153
Multi-Fickian method, 495–496
in Abaqus code and applications, 501
bound water concentration, 498–499
partial differential equations, 498
shape parameters, 499, 500*t*
sorption isotherms, 499–500, 500*f*, 500*t*
Multiway data analysis (MWA), 509, 509*f*
Mycotoxins, 354

N

Nacerdes melanura (wharf borer), 398
Natural castor oil, 225, 226*f*
Natural fibres
advantages, 337
classification, 337, 338*f*
Natural oil based finishes, 224–225, 226*f*
Neutron imaging (NI), 411–413
New wood species, 264
NF environment, 567
Nonstructural purposes, bio-based materials, 250
Nordic Ecolabel, 566
Nuclear magnetic resonance imaging (NMRI), 413, 414*f*
Numerical modelling, 300

O

Object quality, 288
Oil treatment, 213–214
Organisational protection, 229, 229*f*
Oriented strand board (OSB), 52, 57–58, 57*t*

P

Paraffin, 214
Parenchyma, 156–157
Paris agreement, 14
Particle board, 52, 55–56, 56*t*, 169–171
Pattern, 287, 288*f*
Peat
in building structures, 147
chemical properties, 146
current techniques, 148, 148*f*
fire resistance, 146
mechanical properties, 146
mires and peatland, 142–144, 144*f*
producing methods, 145–146, 145*f*
radon protection, 147
rodent resistance, 147, 147*t*
technological properties, 147
thermal and moisture properties, 146, 150*t*
3D printing, 149

Phase-change materials (PCM), 343–344
Phenol, 216–217
Phenylpropane, 25, 25*f*
Pholad borers, 399–400
Physical barriers
  against marine borers, 237, 238*f*
  against termites, 237, 237*f*
Pigmented paints, 219–220
Plaster-based building material
  bacterial growth testing, 393*f*
Plywood, 52, 54–55, 55*t*
Pole buildings, 36
Political issues, 14
Poly-aromatic hydrocarbon (PAH) loss rates, 429–430
Polymer particle dispersion, 227
Polypropylene, 110
Polyurethane adhesive, 40–41
Postframe, 36
Potential hazards
  bacteria, 192
  decay fungi, 188–192, 189*t*, 191–192*t*
  discolouring fungi, 192
  insects, 193–200
  marine borers, 200–201
  moisture, 188
  physical and biological hazards, 201–203
Powder-post beetle, 193–194
Powderpost beetle attack rating, 396*t*
Pozzolanic materials, 362
Prefabrication, 43
Preference test approach, 293
Preservative retention, 210–211, 210*f*
Pressed insulation plates, 154, 154*f*
Pressed peat, 147. *See also* Peat
Pressure plant, 208, 208*f*
Product Environmental Footprint (PEF), 13
Product Environmental Footprint Category Rules (PEFCRs), 13
Propiconazole, 204–206
Protective measures
  covers effect, 233–234*f*
  end grain, 233*f*
  from ground contact, 235*f*
  marine borers, 237, 238*f*
  moisture protection, 230
  physical barriers, 237, 237*f*
  principles, 228–230
  quantification, effect of, 238–239, 240*f*
  shelter effect, 232*f*
  from splash water, 232–233*f*
  steel anchors effect, 236*f*
  termites, 237, 237*f*
  ventilation measures, 230, 230–231*f*
  from water accumulation, 234*f*
  water draining, 236*f*
  from wind-driven rain, 231*f*
  of windows, 232*f*
Pselactus spadix, 398
Psychophysiological well-being, 367
Pulp and paper, 70–73
Pulp washing process, 71
Pyrolysis combustion flow calorimeter (PCFC), 164

Q

Quasi-continuous approach
  of exposure dosage, 267–268, 267*f*
  of material resistance, 268, 268*f*

R

Rattans, 120–124, 120*f*
  fibres, 121, 121*f*
Recycled boards, 60
Reed, 347–348
  composition, 126, 126*f*
  premature decay, in reed thatched roofs, 125
  thatching material, 124–125, 125*f*
  water absorption, 126–127, 127*t*, 128*f*
Reed thatched roofs, 125
Refining process, 72
Reliability analysis, 494
Repelling water method, 213–214
Resin treatment, 214–215
Restorative environmental and ergonomic design (REED), 371–372
Rhinotermitidae, 200
Rigid board, 165–166, 166*f*

S

Sapstain/blue stain, 259
Sapwood, 22–23
Seaweed balls, 154, 155*f*
Sedlbauer's isopleth model, 484–487, 486*f*
Semitransparent finishes, 222–224
Sensorial analysis, 292

Separating function, fire resistance, 316–317
Service life, 289
Service life prediction (SLP), 263
  levels of, 269–270, 269*f*
Shape stability, 252–253
Shipworm, 200
Simulated house test, 422
Single-Fickian model, 495
  in Abaqus code and applications, 497–498
  governing equations, 496–497
Slip resistance, 253–254
Smart bio-based materials, 346–347
Social issues, 14
Softboard (SB), 58, 59*f*
Soft rot decay, 390
Soft rots, 259
Softwood, 22, 23*f*
Soil block tests, 387
Sorghum, 158–161, 160*f*
Sorption isotherm, 28, 29*f*. *See* Moisture storage function
Sphaeroma, 399–400
  test method, 401–402
Stadthaus 9-storey, 48, 49*f*
Stake tests, 421–422
Steel screws, 44, 44*f*
Stegobinone, 195, 195*f*
Stiffness, 253
Strain, 32
Straw
  acoustic properties, 118
  bales as construction material, 114–115, 115–116*f*
  compressed straw board, 119
  fire resistance, 118, 119*f*
  hygrothermal properties, 116–117, 117–118*f*
  mechanical properties, 117–118
  structure and composition, 112–113, 113*f*
Strength/weakness/opportunity/threat (SWOT) analysis, 15, 15*t*
Suberin, 81–82
Submersion test, 415
Sulphite process, 71
Sunflower, 158, 160*f*
Superhydrophobicity, 227
Surface appearance
  lab assessment, 290–291
  visual assessment, 290
Surface finishes
  coating material, 218
  maintenance, 228
  materials, 218
  products, 218–227
Sustainability assessment of buildings 15978EN
  Bionova Ltd, 580–584
  ELODIE, 580
  IMPACT compliant tools, 580
  Tally, 580
Sustainable agenda, 10–11
Sustainable construction, 1–2
Sustainable planning, 11–12
Synthetic paraffin wax, 226–227

T

Take-make-waste economy, 560–561
Tally, 580
Teredinids, 400
  field testing, 424
  laboratory testing, 404–405
Termites
  field testing, 421–422
  laboratory testing, 394–396
Thermal conductivity, 294
  and density, 301–302
  measuring methods, 295–300
  and moisture content, 302–303
  numerical modelling, 300
  and temperature, 304
  and wood orientation, 303
Thermal modification, 32–33
Thermal treatment, 212–213
Thermomechanical pulps, 71
Thermoplastics, 62
Thermoset resins, 63
34-storey Västerbroplan, 51, 51*f*
Timber bridges, 38–39, 39*f*
Top-down approach, 12
Totora plants, 167
Traditional flaxboard, 102, 103*f*
Traditional wooden house, 35
Transient hot bridge (THB) method, 300
Transient hot strip (THS) method, 299–300
Transient hot wire (THW) method, 297–299, 299*f*
Transient plane source (TPS) method, 296–297, 298*f*

Transmission loss (TL), 342
Transparent finishes, 222–224
Tung oil, 225, 226*f*
Twenty-storey apartment blocks, 51, 51*f*
Typha, 159

U

Urbanisation, 10
US-based Green Building Council (USGBC), 8
Use class 3 (UC 3)
  complete sampling, 435, 437*f*
  copper leaching rates, 436, 438*f*
  Cr-Cu ratios, 438, 439*t*
  mean moisture, 437–438, 438*f*
  UV-light-induced chemical reactions, 436
  vertical test design, 436, 436*f*
Use class 4 (UC 4)
  abiotic and biotic aspects, 439
  brown rot degradation, 439, 440*f*
  copper (mg/kg) and compression strength, 439–440, 441*t*
  copper retention, 440
  Cu and Cr, leaching of, 440, 442–443*t*
  humic acid, 439
UV absorbers, 223–224
U-value requirements, 3, 4*f*
UV protection, wood, 222–224, 224*f*

V

Valchromat, 60
Varnish, 222
Vegetal pith
  chemical composition, 161–162, 161*t*
  concretes and blocks, 172–173
  distribution, 158, 158*f*
  hygroscopicity, 163
  morphology, 159–161, 160*f*
  particleboards, 169–171
  sorption isotherms, 163, 164*f*
  sources, 157–159
  thermal degradation, 164, 165*f*
  thermal insulation boards, 164–169, 166–168*f*
  thermal properties, 162–163, 162*t*
Ventilation, air quality, 357
Virgin cork, 80, 80*f*
Visual strength grading (VSG), 457
Volatile organic compounds (VOCs), 140–141, 219, 351–352
  characteristics, 358
  sampling and analysis, 359–360
VTT model, 490–492, 492*t*

W

Wall cladding, 83–84, 83*f*
Washington declaration, 10–11
Waste wool, 136
Water immersion tests, 430–431, 431*f*
Waterproof barriers, 279, 280*f*
Wax, 226–227
Wax treatment, 213–214
Weathered wood samples, 290, 290*f*
Weathering
  cellular level, 503–504
  deterioration processes, 502, 503*f*
  dose-response models, 507–508
  factors influencing, 502–503
  field testing, 435–440
  lab testing, 430–435
  macro level, 504–505
  molecular level, 503
  multiway data analysis (MWA), 509, 509*f*
  non-destructive sensing techniques, 505–506, 506*t*
  partial wetting, 429*f*
  preservative component depletion, 428, 428*f*
  preservative component displacement, 429, 430*f*
  regression models, 508
  tissue level, 504
  validation procedure, 510
  W_{ind} computation algorithm, 506–507
Weight percent gain (WPG), 214–215
Wheat straw isopleth, 117, 118*f*
White-rot fungi, 190
White rots, 259
Whole building assessment schemes
  BREEAM-United Kingdom, 577–578
  DGNB-Germany, 578–579
  HQE-France, 579
  LEED-United States, 578
Wood
  absorbability, 30
  acoustic properties, 31
  applications, 35–39
  in building constructions, 35
  coating, 33

colour, 27
as construction material, 276–277
decks, 38
density, 27–28
durability, 34
elemental composition, 26, 26*t*
fillers, 63–64
fire performance, 34
flour, 63
gloss, 27
impregnation, 33
marine testing, 423–424, 423*f*
material resistance, 265–266, 266*f*
mechanical properties, 31–32
moisture content, 28–29
moisture storage, 406–407
oil treatments, 264
pattern, 27
permeability, 30
polymers, 29
porosity, 28
precipitation, 279*f*
principal directions, 302*f*
properties, 26–32
quality, 34
seismic performance, 35
service life performance, 263–264
specific heat, 30
specific thermal conductivity, 30
stress, 31–32
structure, 22–26
thermal conductivity, 294, 295*t*, 348
thermal diffusivity, 31
thermal expansion, 31
thermal properties, 30
treatments, 32–33
waterproof barriers, 279, 280*f*
Wood and wood-based products, 594–595
biological resistance, 596–597
moisture risk, 598–599
performance, 597–598
service life planning, 599–600
wood-disfiguring fungi, 599
Wood-destroying beetles, 194, 194*t*, 260
Wooden floor, 37, 38*f*
Wooden pillars, 37, 38*f*
Wooden roof, 37–38, 38*f*
WoodExter/WoodBuild approach, 519
Wood facade claddings, 39, 39*f*
Wood floor covering, 567, 568*t*
Wood modification
acetylation, 214
dimensional stability, 211, 212*f*
DMDHEU, 216
furfurylation, 215–216
oils and waxes treatment, 213–214
phenol, 216–217
resins treatment, 214–215
thermal treatment, 212–213
Wood panels, 52–61, 53*f*
future directions, 60–61
Wood plastic composites (WPCs), 603
components, 62–64
in construction sector, 66–67
manufacturing process, 65–66
performance, 67–68
Wool
acoustic performance, 136–139
construction material, 133–136, 133*f*
cortical cells, 128–130, 129*f*
cuticular parts, 128–129, 129*f*
indoor air quality performance, 139–141, 139*f*, 141*f*, 141*t*
insulation, 134–136, 134–135*f*, 137*t*
main fibre, 128–130
microscopic properties, 132–133
morphological composition, 130, 131*t*
surrounding lipid layer, 131–132, 132*f*
thermal performance, 136
ultrasonic disruption, 130
Wool-based insulation, 134–136, 134–135*f*

X

Xylophagaids, 399–400

This page intentionally left blank

WOODHEAD PUBLISHING SERIES IN CIVIL AND STRUCTURAL ENGINEERING

Performance of Bio-based Building Materials provides guidance on the use of bio-based building materials (BBBM) with respect to their performance. The book focuses on BBBM currently available in the European market and presents a broad overview of the topics relevant for application and promotion of these materials in construction.

Chapters cover both 'old and traditional' BBBM since quite a few of them are experiencing a comeback on the market. Each chapter contains a general description and notable properties related to performance and applications. Topics include non-wood bio-based materials, test methods for bio-based materials, modelling, evaluation and standardisation. The chapters analyse in detail the material properties, recommended uses, performance expectancies, testing methodologies and related standards.

The book has been written by leading experts working on each material type and will be a valuable reference resource to those working in the bio-based materials research community, such as architects and agencies dealing with sustainable construction and graduate students in civil engineering.

Dennis Jones, the Chair of COST Action FP1303, has 20 years of experience in wood and bio-based material research and technology. Currently a consultant, as well as being associated with Luleå University of Technology in Sweden and the University of Primorska in Slovenia, he has also worked in the UK, Denmark, The Netherlands and Sweden. **Christian Brischke** is the Vice Chair of COST Action FP1303 and is a Researcher at The University of Göttingen in Germany. He has a prolific publication list in areas linked to protection and performance of bio-based materials.

ISBN 978-0-08-100982-6

9 780081 009826

ELSEVIER

WP
WOODHEAD PUBLISHING
An imprint of Elsevier
elsevier.com/books-and-journals