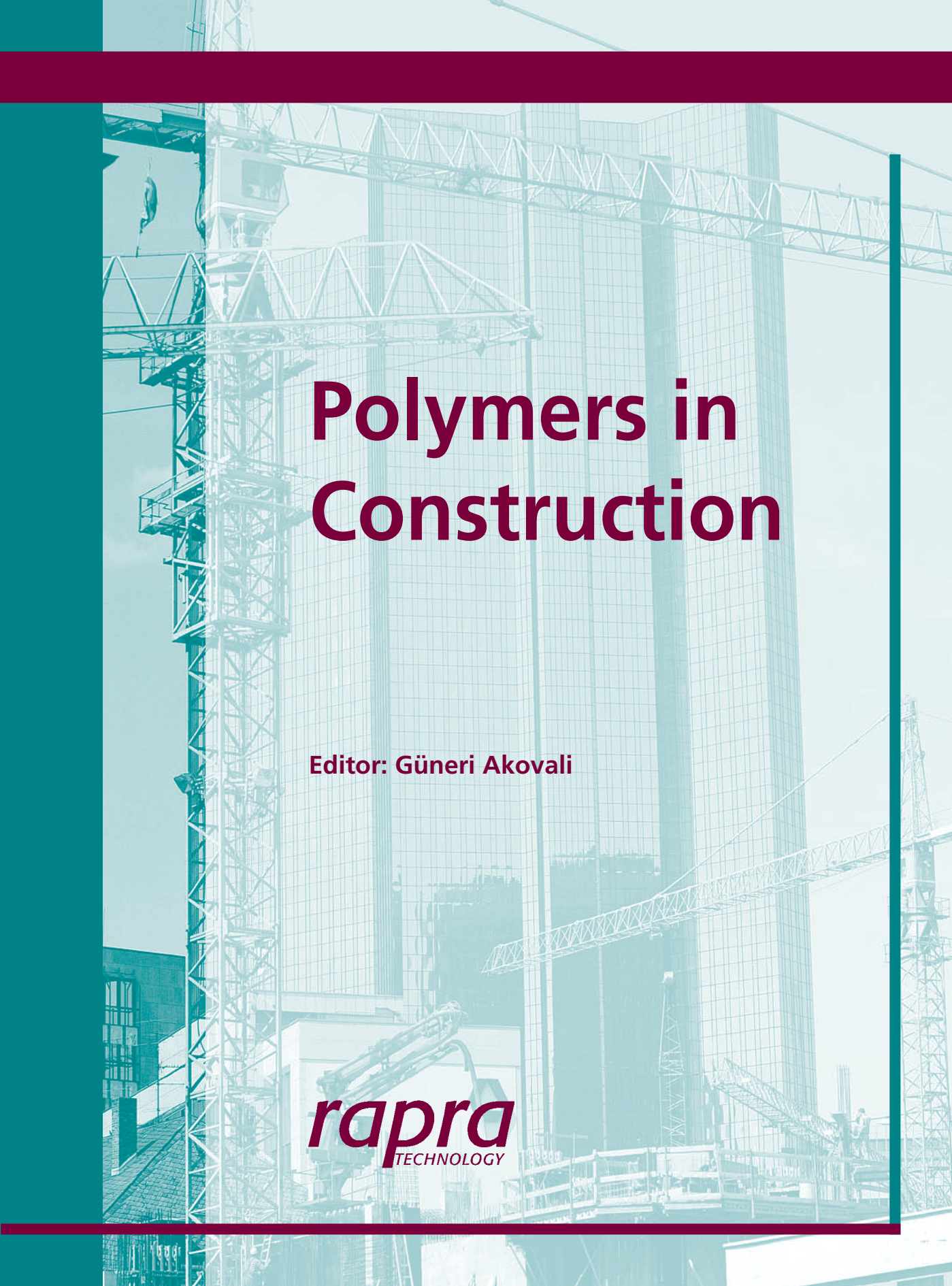

Polymers in Construction

Editor: Güneri Akovali

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Preface

The construction sector is the second highest user of plastics worldwide, although its acceptance by this sector is not yet complete. However, signs are very promising for a much larger share of plastics and rubber in this sector in the very near future. In the EU only, over 6 million tonnes of plastics per year are consumed in the construction sector, and this figure is predicted to increase to 8 million tonnes by the year 2010.

Plastics are used very effectively for various structural and non-structural applications in construction, because they provide long-lasting and the least problematic solutions. They are light in weight with perfect durability and toughness. Plastics provide ease of installation and assembly with cost effectiveness and low maintenance. It is now a very common practice to use plastics and rubber in exterior and interior applications, and in energy conservation. They are used for thermal, as well as for water, acoustic, electrical and retrofit insulations. They are very successfully applied for retrofitting and rehabilitation, in addition to in flooring, piping and conduit applications. Plastics and rubber are very attractive choices for window profiles and doors, as well as for seals, gaskets, membranes and claddings, fencing and decking, isolation foams and shock absorbing materials. The list for these and other applications of plastics in construction is long, and grows ever longer.

This book is designed as a handbook to provide some basic, up-to-date information and whenever possible information on practical issues, for this very promising material and its applications in construction. It is hoped that, it will give enough insight both to the newcomers to the industry and to the technical personnel already working in construction sector and that it will help to further promote the use of this material which is neglected somewhat because of the unkowns and negligence.

The book has 13 chapters, each prepared by a group of experts from different parts of the world. The first chapter, the introduction, provides the basic information. A review of the use of plastics in construction looking at its past and the future trends is covered in detail, in Chapter 2.

The use of plastics specifically in building construction is discussed in five sections in Chapter 3, by considering their structural, secondary structural and non-structural applications and also their use in polymeric coatings and EPDM membranes. Systems for condensation control is the theme of Chapter 4.

The use of plastics in civil engineering, is covered, in general, in Chapter 5. In this chapter, geotechnical engineering applications of plastics and their use in concrete, with their repair and strengthening applications, are discussed in depth.

To give some insight for this relatively new material, namely plastics, some basic information is presented in Chapters 6, 7 and 9. The brief chemistry and mechanics of plastics materials and composites are discussed in Chapter 6, along with some information on the additives commonly used, while in Chapter 7, a review is presented of the properties related to use of plastics and polymer composites in construction. To complete the plastics circle, processing of plastics and composites are reviewed in Chapter 9.

Chapter 8 concentrates on sustainable construction. Wood-plastic composites are being used in construction at an increasing rate. Lignocellulosic fibres and plastic composites are extensively discussed in Chapter 10.

Rubber and rubber concrete is an additional issue that should be considered in the book, because rubber is considered to be a different material, although it is a polymer and used in the construction sector at large. Thus, rubber concrete is the subject of Chapter 11.

There has been a growing interest in health issues relating to the use of plastic construction materials, for some time, and especially on their effect on indoor atmospheres, causing the so called 'sick building syndrome'. PVC is the one plastic that has been most critisised. Some general issues regarding health problems are discussed in Chapter 12.

Chapter 13 presents some definitions related to the subject.

I would like to thank specifically to each of the contributing chapter editors for preparing such a fine work so skillfully, for being timely and co-operative at all times.

My special thanks are due to the commissioning editor, Ms. Frances Powers of Rapra Technology Ltd., for her ever-encouraging efforts as well as unceasing support and for being so cooperative at all times.

I must also thank Claire Griffiths, the editorial assistant, who has done a lot of the corrections to the book and Stephen Barnfield, who was responsible for typesetting the book and designing the cover and Geoffrey Jones who compiled the index. They all did a lot of work to get the book ready for publication, and certainly without them the book would not have been completed in time, so nicely and professionally.

As a final note, I enjoyed editing the book a lot, and I hope that the readers will also enjoy reading and having the book, and consider it as a valuable source of information.

Professor Guneri Akovali, Editor

August 5, 2004

1 Introduction

Güneri Akovali

Plastics are used greatly in various parts of construction. In fact, the construction sector is the second highest user of plastics (after packaging). In 1999, 18% of total plastics consumption was due to this sector which totalled to over 6 million tonnes only in the EU (**Table 1.1**). There are many reasons for the increasing use of plastics in construction, both for structural and non-structural applications. Firstly, they are light and hence have excellent strength to weight ratios, they have perfect durabilities and toughness, proper cost effectiveness and low maintenance, and perfect insulating properties, all of which make them a very attractive choice as a construction material (**Table 1.2**). Plastics are used in the construction industry because:

- They provide long-lasting solutions: they are durable, strong, tough and corrosion resistant with perfect insulation properties (water, heat, noise and vibration).
- They are light in weight and their installation and assembly is easy.
- They can be used for creation of stylish, hygienic modern designs, i.e., in kitchens and bathrooms, and for retrofitting and rehabilitation.
- They can be used for the design of the future applications: i.e., as smart materials, to produce climate walls to regulate internal temperature, in solar energy generation systems, in activated glazing systems which can become transparent or opaque, and to produce earthquake-proof buildings.
- Special light transmitting plastics with high clarity and shatter resistance are suitable for use indoors and outdoors.

Plastics in construction are mainly used for insulation (thermal, water, acoustic, electrical and retrofit insulations) as well as for flooring, piping and conduits, and as various profiles (in windows and doors), as membranes and cladding, and they are applied as seals and gaskets The use of plastics in the construction sector (currently, 23% of all plastics consumption in UK) is expected to grow even more in the coming years mainly because of the increased emphasis on energy efficiency in buildings. Consumption of plastics by the building and construction sector in Western Europe is predicted to rise by

Table 1.1 Some applications of plastics and rubbers in the construction and building sector		
In the building envelope	As fascia boards	In paints and varnishes
As roofing materials	As cladding panels	As adhesives
For waterproofing (as coats and membranes)	As laminates for formwork and decoration	As sealants
In insulation (thermal/ electrical/soundproofing/)	As interior fittings	As flexible foams for upholstery
As barrier films	In decking and railing	As fibres (for carpets and fabrics)
As window frames, doors	In plumbing, fixtures, pipes, gutters and drainage systems	As anti-vibration mountingsand seismic isolators
As concrete additive/impregnation and reinforcement	As geotextiles, geogrids, geomembranes and geomatrices	As plastic fencing
In glazing	As wallpapers	In general retrofitting and rehabilitation of buildings
For floor coverings and resilient flooring	As plastic lumber	For retrofitting of bridges, aerial walkways and foundations
(a) EXTERIOR use of plastics are mainly in: Roofing, roof-drain systems, building envelope, exterior trim, cladding and siding.		
(b) ENERGY CONSERVATION applications of plastics are mainly in: Wall/ceiling insulations, radiant barriers and structural-insulating sheathing, heat-ventilation and air conditioning systems (HVAC).		
(c) INTERIOR use of plastics are mainly in: Windows and doors (frame, foam-core centers, gaskets and sealants), glazing, piping, fittings and fixtures, flooring, counter tops, coatings, paints, interior trim, furnishings, carpets.		
(d) Plastics and rubbers as CONSTRUCTION PRODUCTS are used mainly for: Pre-engineered load bearing beams/joints, integrated wall systems, drywall alternatives and accessories, sound/fire party walls, structural/insulating sheathing in house building, and fencing/decking, as geotextiles, geomembranes, geogrids and geomatrices, in bridge decks and fibre-reinforced plastic (FRP) bridge construction, retrofitting/rehabilitation of old concrete structures, asphalt additives, crash/noise barriers, in civil engineering applications.		

Table 1.2 Some of the plastics used commonly in construction	
Application(s)	**Plastics (and rubbers) used**
Glazing	Acrylics, PMMA with an acrylic elastomeric component), polycarbonate (PC), glass reinforced plastics (GRP) (roof)
Roofing	PVC, chlorinated polyethylene (CPE), polyvinylidene chloride (PVDC), GRP, PC, ethylene-propylene-diene monomer (EPDM), expanded polystyrene (EPS) (sheet), reinforced styrene-butadiene-styrene (SBS) copolymer
Cladding (siding)	GRP, PVC, foamed unplasticised PVC (PVC-U), acrylonitrile-butadiene-styrene copolymer (ABS) as a blend of ABS/acrylic/PVDF
Suspended ceilings	Acrylic, GRP, PS, PC
Walls and wall partitions	GRP, polypropylene (PP), PVC, PVC (with acrylic or PC), EPS (sheets and fill-in)
Wall papers	Mostly PVC
Window frames and doors	PVC, foamed PVC (wood substitute), ABS (co-extruded with vinyl modified ASA or polyolefins modified styrene acrylonitrile copolymer (SAN) - glass-fibre reinforced plastic (GFRP), composite based, ABS (thermoformed panels for high quality doors and window profiles)
Seals, sealants, gaskets and adhesives	PU, epoxy, thermoplastic elastomers, silicones
Paints (exterior and interior)	PU, acrylics, siliconics
Non-structural insulation foams (heat)	Foams of: PU (rigid), EPS, expanded polyethylene (EPE), phenolics, furanes, PVC, polyisocyanurate (PIR), urea formaldehyde(UF) (indoors)
Other insulation foams (water/frost)	PU, PS, polyolefins [polyethylene (PE), polypropylene (PP)], PVC
Insulation (noise and seismic vibrations), sonor foams	Laminates of rubber (mostly natural/chloroprene), polyphenylene oxide (PPO, UF foams, open cell foams of PU, PIR, PS
Electrical insulation (wiring, cables and conduits)	Mostly PVC, polyolefins (PE, PP) (foamed and non-foamed)

Table 1.2 Some of the plastics used commonly in construction (*Continued*)	
Application(s)	**Plastics (and rubbers) used**
Structural-engineering foams, sandwich panels (SWP)	Foams of: (PIR), polyolefins (PE, PP), modified PPO, PC, ABS, high-impact PS, sandwiched PU (for load bearing applications)
Barrier films for building envelope	Polyolefins (PE, PP), PVC, aliphatic polyamides, polyethyleneterephthalate (PET)
Plumbing (piping for cold/hotwater, drainage and gas distribution and floor heating systems)	Mostly PVC, CPVC (for large diameter industrial pipes), MOPVC, PE-HD and LD and other types, ABS, PP, GRP, polybutylene (PB), acetal, polyolefins (croslinked PE (XPE) (for floor heating)
Flooring, tiles	PVC and it's copolymers, epoxy, PU
As an additive to cement and reinforcer to concrete	Polymer modified concrete (PMC), polymer concrete (PC), polymer impregnated concrete (PIC), fibre-reinforced plastic (FRP) rebars
As an additive to asphalt and cement	Rubber granulates
Plastic lumber and wood substitutes	Waste (PET), HDPE, PE (HD /LD), all with wood fibres) and co-extruded capstock (ABS/PVC with. PVDF cover)
Geotextiles, geocells, geomembranes, geomatrices, geogrids	PP, HDPE, PVC, polyesters (thermoset), synthetic rubbers
Plastic fencing, decking and railing	PVC
Surfacing (work, floor and table surfaces)	Polyesters (thermoset)
Retrofitting and rehabilitation	Fibre reinforced thermoset systems (i.e., glass fibre/carbon fibre reinforced epoxy/polyesters)
MOPVC: Modified PVC CPVC: Chlorinated PVC ASA: Acylonitrile-styrene-acrylonitrile block copolymer PVDF: Polyvinylidene fluoride	

more than 60%, to almost 8 million tonnes by 2010. Germany is the largest user of plastics in building and construction so far in Europe (27%), followed by France (18%) and the UK (14%). In the Netherlands, 25% of the country's total plastics consumption is in this sector (which is 5% of Europe's use).

Tables 1.1 and 1.2 present some examples of plastics and rubbery materials used typically in building and construction applications.

Additional information about some of these applications as well as their historical evolution are presented in Chapters 2 to 6 of this book.

In the plastics construction materials list, the biggest share belongs to polyvinyl chloride (PVC) (by 55%), followed by polystyrene (PS) (15%), polyolefins (15%), polyurethanes (PU) (8%), and two others, mainly poly(methylmethacrylate) (PMMA) (7%) [1].

If the various uses of plastics materials in construction is considered, a number of reasons for these uses can be postulated:

- Plastics help to conserve energy. Polymeric foam insulation, vinyl siding and vinyl-framed windows all help to cut energy consumption and lower the heating and cooling bills. Polymeric foams are used effectively for insulation of roofs, walls (either as cavity wall, or internal and external walls), heat pipes and floors. The success of these applications is certainly due to the positive results obtained as well as to the favourable ratio of cost to results. One study shows that more than 60% of all domestic energy consumption is for space heating [3], and that improvement in thermal insulation, (i.e., by cavity and loft insulation), results in at least a 35% saving. Since cellular plastic materials (both foamed and expanded, with closed cell structures) are the most effective heat insulators, with lowest rates of heat transfer values (as characterised by U, being 0.26-0.4 W/m^2-K for polymers versus 1.4-3 W/m^2-K for brick and concrete), they provide considerable improvements of thermal efficiencies in houses. It is estimated by the US Department of Energy (DOE) that only the use of polymeric foam insulation in homes and buildings is expected help to save about 60 million barrels of oil per year, worldwide. The extra cost of insulation by the use of cellular plastics is shown to be recovered within a maximum 6 year period [2]. In Europe during the last three decades, use of plastics insulation has increased by more than 1250%. It is also estimated that the use of plastics in construction will reduce annual fuel consumption (for a 100 m^2 apartment from 2,000 litres to 300 litres), simply by replacing traditional building components with their equivalent plastic components, (i.e., by using triple glazed PVC window frames and polymeric window coatings, which do not only reduce heat loss from the house, but also allow solar gain). In fact, PVC use in window applications and floor coverings increased on average by 5,000% and 120%, respectively, worldwide, during the last three decades.

The 'three-litre house' equivalent of only three litres of heating oil per square meter of living space a year and a more than 80% reduction in emissions of carbon dioxide (as realised by BASF for ultramodern low-fuel-consumption apartment buildings), is a reality and is achieved by use of optimal thermal insulation with newly developed construction materials, a special air-exchange system and a fuel cell. In a 'three-litre house', i.e. a 100 m^2 apartment, the annual heating costs will be less than EUR 150 instead of EUR 1,000.

- Polymers also provide good insulation against water penetration and act as a moisture barrier. Dampness can easily threaten a property, and the solution to water penetration in external walls as well as stopping the flaking, cracking, crazing and blistering on external and internal walls poses a very important issue, all of which can be overcome by using proper polymers (as a coat or by use of closed cell cellular plastic materials).

- By using polymers, proper sound insulation can be achieved easily and effectively. Cellular plastic materials (with open celled flexible structures) are shown to be very effective in sound insulation (either for impact noise from footsteps and movement on the top floors of a building, which can usually be eliminated by floor insulation, or airborne noise, which is from noises in the neighbourhood or the street, and which needs wall/party wall insulation for its elimination). Open cell flexible cellular plastic materials also provide acoustic insulation at high frequencies.

- The toughness and noise absorbing properties of plastics are always appreciated in construction applications. The use of plastic piping in homes leads to non 'water-knocking' systems, which is a major problem with other conventional pipes. Plastics use in piping has tripled during the last three decades in Europe, and is expected to grow even more in the years to come. Plastic parts and insulation have also helped to improve energy efficiency in appliances such as refrigerators and air conditioners by 30 to 50% since the early 1970s. In addition to the gain from their noiseless running: they run more quietly than earlier designs that used other materials. Usually closed cell foams based on rigid PU blended with more viscoelastic polymers possess good vibration-damping properties [1]. Vibration-damping is of environmental importance since noise is radiated by the vibration of an object and it can be converted into heat by polymeric materials like foams, rather than being radiated to the air as noise.

Application of (carbon fibre) polymer composite blankets as vibration damping stabilisers for bridge columns, seismic retrofits and structural reinforcements are recognised in recent years, while rubber seismic bearings have been used for a long time.

The noise absorbing capacities of polymers used in construction are discussed briefly in Chapter 3.

As regards the toughness of plastics, the catastrophic Northridge earthquake (6.7 on the Richter Scale) on January 17, 1994 can be mentioned: it was found that within the three pipe materials used (asbestos cement, PVC and steel), PVC outperformed the others. In 30 minutes, while hundreds of mains and service lines broke, none of the lines made of PVC, about half of the city's total system of approximately 430 km, failed.

It is said that, there would be no electricity in our homes if there were no plastics materials available to coat and insulate the wires. As shown previously in the Tables, plastics are also used as electrical insulators, i.e., in electrical wires. Hence, in their absence, life would not be that easy, because electricity would not be able to be delivered that easily; and so plastics certainly help to improve the quality of life.

Plastics have lower densities than other structural materials. This results in lighter materials in construction. The roof of the 'Stade de France', in Paris, which hosted the Football World Cup, for example, is the world's largest adaptable Olympic stadium, which is made of 60,000 m^2 of plastic membrane weighing 75 tonnes, in comparison to the 13,000 tonnes of the whole roof structure.

Improved concrete structural members such as columns and piles can be manufactured with exterior and interior sub-members of fibre-reinforced-plastics (FRP). FRP components impart greater compressive, flexural and shear strengths in addition to ductility and durability, to the concrete structural member. Use of a FRP exterior shell to control plastic shrinkage cracking of concrete has been known for a long time. The FRP exterior shell can also serve as a form for casting the concrete during fabrication, and during use, it prevents, or retards, the intrusion of moisture and any other possible environmental degradation of the concrete, hence prevents, or retards, corrosion of any steel reinforcement or steel structural member(s) embedded in the concrete. This is particularly critical in regions where concrete is damaged during freeze/thaw cycles, i.e., for houses and bridges especially in coastal areas and in earthquake zones. In fact, this is a general universal problem and according to Antonio Nanni, a professor of civil engineering at the University of Missouri-Rolla, almost half of the 575,600 highway bridges in the US are structurally deficient or functionally obsolete [4], which could be retrofitted easily by a band-aid solution: by applying the exterior carbon fibre reinforced epoxy system. This composite is eight times stronger than conventional steel bar concrete, and it can be formed into sheets of prepregs and can easily be wallpapered over damaged concrete foundations and structures.

A number of different applications for the use of polymers with concrete and its various retrofitting and rehabilitation examples are presented in Chapters 4, 6 and 8 of this book.

Replacement of steel rods ('rebars' - short for 'reinforcing bars') by polymeric fibres (to produce FRP Rebars) is a very effective way to eliminate the problem of corrosion of steel

rods in concrete, and also to impart improved strength, which has been successfully applied in many construction applications so far. The use of ultra-high strength polymeric fibres that are at least six times stronger than steel, some 20% lighter and are non-corrosive, non-magnetic and durable, can also be combined with detecting sensors (intelligent) giving 'smartness' to the structure and hence remote monitoring of the structure. In these systems, the load-bearing capacity of FRP Rebar lies in the polymeric fibres: they bear the load, and the actual purpose of concrete is to hold them in place, hence help to reinforce the rods.

FRP composites are considered as a major breakthrough in the construction sector, and one of its applications as 'FRP Composite Bridges' is worth mentioning, (i.e., a pedestrian bridge across a railway line for an electric high-speed train in Spain, several composite footbridges and road bridges in UK, and the bridge between Scandinavia and Denmark).

Although its applications are so versatile and promising [5], plastics as a construction material and its composites are not as well known as the other conventional construction materials, such as steel and concrete. Very few architects, engineers or structural engineers have extensive experience in working with structural or non-structural use of plastics and FRP profiles.

In this context, general information about polymer composites are presented in Chapters 5 and 8, while more detailed information for FRP rebars and retrofitting/rehabilitation of concrete as well as several applications are presented in Chapters 2, 4 and 6.

The use of wood plastic composites (WPC) [6] is gaining importance in construction sector, and is discussed in Chapter 9.

To the existing all-plastic (or most-plastic) 'concept' houses, a 'NanoHouse' concept has recently been realised, which takes us from 'imagination' to 'reality', as presented briefly in Chapter 2.

Application of 'smart material' concepts is certainly helping to increase the living standards and comfort, as well as monitoring a building's health to help to prevent disasters.

The variety of applications of plastics materials in the construction and construction-related areas is almost never-ending, and every day there are several new ones appearing as structural or non-structural applications. One such application is their use as light composite decks in elevated freeways to accommodate private cars hence increasing road capacity during peak hours traffic in Netherlands (in Netherlands, roads can only be extended in width and therefore it is logical to look at elevated highways to speed up traffic flow), while another is the maintenance-free estate fencing composite made of polypropylene with glass fibre (which is economical and does not need any painting at all). It is almost impossible to mention and cover all of existing and new applications of plastics in construction but I believe that we have done our best to in this handbook.

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2 The Use of Polymers in Construction: Past and Future Trends

Dorel Feldman and Güneri Akovali

2.1 History of Polymeric Materials

The use of polymeric materials started within the first stages of the evolution of mankind, who had used a wide range of macromolecular products such as: clay, stone, wood, leather, cotton, wool, silk, parchment, papyrus and later on paper. Paper fabrication marked the beginning of the chemical processing of the natural polymers that over time were developed more and more. When man protected himself against wind and weather he constructed his primitive buildings of wood, bamboo, leaves, leather and fabrics, all of these materials are made of natural polymers.

Natural organic polymers dominated the existence and welfare of all nations, virtually nothing was known about their composition and structure. In each area: food, clothing, transportation, communication, housing and art, highly sophisticated craftsmanship developed which was sparked by human intuition, creativity, zeal and patience and led to accomplishments which deserved the highest admiration of generations that followed.

Nowadays polymers have become an increasingly important part of the general group of engineering materials. Their range of interesting properties and applications is at least as broad as that of other major groups of materials, and ease of fabrication frequently makes it possible to produce finished items very economically. Important industries such as those for plastics, fibres, rubbers, adhesives, sealants, coatings and caulking compounds are based on polymers.

Natural polymers were the first basic substances used, starting in the 19th century, for obtaining the first plastic materials. During the 20th century, chemical processes permitted the production of a wide range and high volume of synthetic polymers. They are now basic materials in construction, automation, transportation, packaging, electronics, etc.

Between 1862 and 1866 in England and the USA, nitrocellulose was produced by treating cellulose with nitric acid, which in 1872 was plasticised with camphor to become the first plastic material known as celluloid [1].

In about 1897, galalith (gala = milk, lithos = stone) was produced in Germany by reacting casein, a milk protein, with formaldehyde [2].

Whereas celluloid was the first plastic material obtained by chemical modification of cellulose, the phenol-formaldehyde (PF) resin was the first commercially successful synthetic plastic. This phenolic plastic was discovered by L.H. Baekeland in Belgium in 1907, and Bakelite was produced industrially in 1910. Baekeland used the term resole to describe PF resins made with an alkaline catalyst, and those made with an acidic catalyst were called novolac. The ability of formaldehyde to transform some products in resinous materials was observed by Butlerov (1859) and Bayer (1872) [3].

It is of interest to note that Eastman used Bakelite for the Kodak camera in 1914 and that the Hyat Burroughs Billiard Ball Co., replaced celluloid with bakelite for its billiard balls in 1912 [4]. The commercial development of the PF product is considered to be the beginning of the truly synthetic plastics era, and of the plastics industry, although cellulose nitrate had been known and in use for some time. The first synthetic rigid cellular plastic was produced accidentally, also by Baekeland in 1909, but the first commercial foam was sponge rubber [5].

The first aminoplast based on urea-formaldehyde (UF) was obtained and patented in 1918 by John through the polycondensation of urea with formaldehyde, although this reaction was first described in 1884 by Tollens [4]. Unlike the phenolics, the UF could be moulded into light-coloured articles and they rapidly achieved commercial success. Paper impregnated with UF resin was used as an outer surface layer of decorative laminate in 1931, and the polycondensation of melamine with formaldehyde led to a new aminoplast resin in 1933 [5].

Unsaturated polyester (uPES) resins based on phthalic anhydride were obtained in the 1930s and were known as alkyd or glyptal resins. Crosslinked with polystyrene (PS) they were, and are still used, for fibre impregnation to produce plastic composites. uPES is among the four most important thermosetting resins besides PF, UF and epoxy (EP) resins and nowadays they represent about 20% of the total volume of thermosets [6].

Polyvinyl chloride (PVC) was first observed as long ago as 1838 by Regnault [7] and first patented in 1912 when Klatte used sunlight to initiate the photo polymerisation of vinyl chloride (VC). In 1926, Ostromislensky patented flexible film cast from a solution containing the polymer and a plasticiser. The phthalate plasticisers were introduced in 1920 and 1922. The first patent on a mouldable plasticised PVC (PVC-P) was granted to BFGoodrich in 1932. Later on the Carbide Company patented copolymers of VC with vinyl acetate (VAc) that are still in use today [1].

In the early 1930s, PVC-P was commercialised by companies like DuPont, Union Carbide, Goodyear, BF Goodrich in USA and IG Farbenindustry in Germany.

Dynamite Nobel AG introduced PVC flooring in Europe in 1934 under the trade name Nipolan. In USA the same product manufactured by Carbide and Chemical Co., was named Vinylite. In England in 1943, ICI and Distillers Co., commenced pilot-plant production of PVC, a material then in demand as a rubber substitute for cable insulation. After the war, developments were concerned largely with PVC-P, handled mainly by extrusion, calendering and paste techniques.

In 1931, Fawcett and Gibson obtained polyethylene (PE), a plastic which showed excellent electrical insulating properties and chemical resistance. Its industrial production started in 1939 [8]. The first application was as underwater cable insulator.

During the 1930s the styrene monomer was obtained and used first in copolymers with elastomeric characteristics [7]. In 1938 several tonnes of polystyrene (PS) were obtained [9].

In the same period polymethyl methacrylate (PMMA) was produced, in 1933 by Rohm and Haas in Germany for aircraft glazing and for a wide variety of applications particularly where transparency and/or good weathering resistance is important [2].

The first polyamide (PA) with the trade name Nylon was developed by Carothers as a fibre in the mid 1930s, and as a moulding plastic. The first fibre known as Nylon 66 was obtained commercially in 1939, and the production of PA plastic started later in 1941 [10].

The discovery of fluoropolymers by Plankett, started in 1941 with polytetrafluoroethylene (PTFE). The most important polymers of this group are the homopolymers of tetrafluoroethylene, trifluorochloroethylene, vinyl fluoride and various copolymers based on these and other monomers [11].

In 1946, Whinfield and Dickson in England discovered saturated polyester (PES). Nowadays polyethylene terephthalate (PET) produced first by ICI in 1955, is used as a plastic and for films and fibres [12].

In 1937, in Germany, IG Farben started the development of polyurethane (PU) and in 1947 Bayer published an impressive account of the synthesis of PU and polyureas from diisocyanates and dihidroxy or diamino compounds, respectively. Later on in 1961 the PU were found to be useful for the production of plastics, foams, adhesives, fibres and corrosion resistant coatings [13].

In the 1950s, high density PE (HDPE) was marketed. Shortly afterwards in 1953 Ziegler and Natta independently developed a family of stereospecific transition-metal catalysts that led to the synthesis and commercialisation of HDPE as well as isotactic polypropylene

(iPP) as major commodity plastic. The production of this iPP began in Italy, the Federal Republic of Germany and USA in 1957. Polyolefins soon became large tonnage thermoplastics [9, 10, 14].

In 1956, Schnell mastered in Germany, the technical process of producing polycarbonate (PC) which had first been synthesised in 1898 by Einhorn [11].

In the same period styrene-acrylonitrile (SAN) copolymer (1954) and polyacetals (1956) were synthesised for the first time.

The next two decades saw the development of new polymers such as: thermoplastic PU (1961), aromatic polyamides, polyimides (1962) polyaminimides (1965), thermoplastic elastomers (styrene-butadiene block copolymers in 1965), ethylene-vinyl acetate copolymer, ionomers (1964), polysulfone (1965), phenoxy resins, polyphenylene oxide, thermoplastic elastomers based on copolyesters, polybutyl terephthalate (1971) and polyarylates (1974).

By the early 1970s, PVC was being manufactured in a large number of countries and was contending with polyethylene (PE) for the title of the world's number one plastic material, in terms of consumption [9].

PVC is used for a large number of items for the construction industry such as: pipes, fittings, tiles for flooring, window frame profiles, sidings and gutters, etc.

After 1980 continuous growth was recorded with the development of a number of high performance polymers that could compete with traditional materials such as: polyetheretherketone, polyetherimide (1982), polyamide 4,6 (1987), syndiotactic PS (1989), metallocene polyolefins, polyphthalamide (1991), styrene-ethylene copolymer, syndiotactic PP in 1992 and nanocomposites [15].

In the growth of polymeric materials in the last decades, plastics are the leader followed by fibres and elastomers.

2.1.1 Plastics in Building

Polymers have been used in construction since as long ago as the fourth millennium BC, when the clay brick walls of Babylonia were built using the natural polymer asphalt in the mortar. The temple of Ur-Nina (King of Lagash), at the site of Kish, had masonry foundations built with mortar made from 25-35% bitumen (a natural polymer), loam, and chipped straw or reeds. The walls of Jericho were built using bituminous earth in about 2500-2100 BC. Other historic applications of bituminous mortars in construction

have been identified in the ancient Indus Valley cities of Mohenjo-Daro and Harappa around 3000 BC, and near the Tigris River in 1300 BC. Many natural polymers have been used in ancient mortar including albumen, blood, rice paste and others [16].

The diversity of their properties and the possibility of adapting these properties to the job at hand, have enabled plastics to gain a real advantage over other building materials. Whilst as early as 1959 the value of plastic materials was a considerable 5% of all building materials, by 1971 it had surpassed 12% and has reached 20% in 1995 [17]. Contemporary construction industry makes used of a wide variety of plastic materials and composites.

2.1.1.1 Flooring

In the 1850s Walton invented *linoleum* (linum = flax, oleum = oil) by applying linseed oil onto cloth. The first replacement of asphalt floor tile came only in 1932 in the early form of what was to become the vinyl-asbestos floor tiles. Later on PVC-P and some VC copolymers proved to be tough and abrasive resistant, essential requirements for good resilient flooring. Because the plasticiser originally used for PVC tiles has led to straining problems, the use of internal plasticisation through the copolymerisation with VAc was implemented in the formulation of the tile [18].

Heavy-duty, lightweight PP duck boarding provides a versatile, easily cleaned work platform, increasing operator comfort and safety. PP flooring is non-corroding and resistant to bacteriological attack [19].

The epoxy polymer (EP) normally used as an adhesive and coating is applied as covering on a sub-floor, providing a durability of over 25 years.

The growth of seamless floors has had an exciting and profound effect on both the PU and flooring industries [18].

2.1.1.2 Roofing

From the first introduction of plastic materials into the roof membrane in Japan and Europe as the sheet (single-ply membrane) or liquid systems, in the late 1950s, they have replaced the conventional hot-applied, built-up bituminous membrane. Single-ply membrane was introduced in USA only in the mid 1960s.

West Germany developed a single ply polyisobutylene (PIB) membrane in 1957, a single ply PVC in 1959 and a plasticised PVC sheet for flooring was trailed for areas of light traffic in 1962 and has been gradually improved [21].

Polymer modified bitumen (Modbit) was developed in Italy around 1960 using atactic PP. The use of such composite systems in USA began during the mid 1970s. These systems based on PP or styrene-butadiene-styrene (S-B-S) block copolymer have used, as reinforcement non-woven fibreglass or PET.

Today thermoplastic roofing systems tend to be lighter in colour, which can add value in terms of aesthetics. They are especially popular in multitiered roofing that can be seen from above the building by occupants or neighbours. The two most common chlorinated hydrocarbon thermoplastics used for roofing are PVC and chlorinated PE (CPE). CPE, a thermoplastic elastomer has rubber-like elasticity, is easy to install (like PVC-P), and it has a better weatherability than the latter. CPE was first used for roofing in 1967. The majority of today's roof membranes are offered in an uncured composition and are reinforced with PES fibres [22]. Some elastomers are also used as roofing materials.

2.1.1.3 Insulating Materials

The history of the science and technology of synthetic foams can be traced from the late 1920s with latex foam. The technologies evolved at that time reached the trial stage in the 1930s. Among rigid foams, low density products were first obtained from special phenolic resins. Before 1942 PF foams had little commercial value. In the USA, the Union Carbide Company initiated development work on low density PF foam as early as 1945.

UF foams were developed as early as 1933. UF is one of the oldest of the cellular plastics. Discovered in 1933 it has been commercially available in USA since the 1950s. The primary uses have been in retrofitting existing walls in residences and within the cavities of new masonry walls, in both residential and commercial buildings. Because of formaldehyde release, many countries have banned the use of UF foam for thermal insulation.

The first patents for cellular PS were obtained in 1931 in Sweden and in 1935 in the USA. Only in the early 1940s did PS foam become commercially available. In the UK, PS foam was made in 1943. In the same year in USA under the trade name of Styrofoam large extruded logs were obtained [24, 25]. The first extrusion technology for producing PS foam was developed in the early 1940s through the early 1950s, and became the current extrusion process for its manufacture. Moulded expanded, extruded PS foam sheet and expanded PS loose-fill packaging materials were developed in the mid-1950s [25].

The rigid PU foams were developed in Germany during the early 1940s by Bayer [26]. During World War II work in the laboratories of Farbenfabriken Bayer, led to the development of both rigid and flexible PU foams. These products were accepted in the USA only after the war. The entry in 1957 of PU grade, polyether-polyol brought about a major change in PU foam technology and markets.

The preparation of rigid polyisocyanurate (PIR) foam was first described in 1961 and developed in Japan in 1966 [13].

These foams are characterised by higher thermal resistance, low smoke density rating, lower thermal conductivity and higher friability than rigid PU foams. More recent chemical modification (cyclic imide groups, carbodiimide groups, etc.), of PIR foam provides relatively low friability and excellent thermal stability.

DuPont in USA disclosed a process for the preparation of expanded PE in 1942, using nitrogen as a blowing agent. In 1945 carbon dioxide was used instead of nitrogen. Commercial production of expanded PE as an electric cable insulation started in 1950s. In 1958 chlorofluorocarbons (CFC) were introduced, and foamed PE insulation was based on high pressure, low density PE (LDPE) [24].

2.1.1.4 Glazing

The basic technique of using domes formed from acrylic sheet as skylights was developed in the 1950s and represented one of the earliest commercial applications of acrylic plastic.

Flat glazing is one of the largest architectural applications for transparent plastics. The need for impact resistance is the main reason for turning from glass to plastics in glazing.

The uses of acrylic and polycarbonate (PC) in architecture started in the 1960s. The World Fairs of 1964 and 1967 in New York and Montreal, respectively, provided timely opportunities to demonstrate on a large scale the earliest examples of plastics as materials for enclosures. Today, flat glazing represents one of the largest architectural applications for transparent plastics [27].

2.1.1.5 Window Frames

Germany produced an unreinforced, all vinyl window in 1960 [28]. The PVC window frame profiles market in West Germany has undergone dynamic growth since 1970 [29].

In 1978 the European market used 10% of the windows made of rigid PVC; in 1988 PVC window profiles having an acrylic impact modifier reached 45-50% of this market [9, 30].

2.1.1.6 Sidings

A rigid PVC siding die built in 1957 and believed to be the world's first, remains on display in Columbus, Ohio. In 1963, three companies commercially introduced solid

vinyl siding at nearly the same time (one in Canada and two in USA). After 10 years from the first production, vinyl siding had become accepted.

The improvements relating mainly to colour resistance and impact retention allowed rapid growth in the vinyl siding industry by the late 1970s. By mid-1982 most major aluminum siding producers were also manufacturing vinyl sidings [31, 32].

2.1.1.7 Plumbing

Most thermoplastics are extruded as pipe, and moulded as valves and fittings. Poly vinylidene chloride was extruded and used to a limited extent prior to 1940. The techniques developed for this pipe were adapted to rigid PVC pipe in Germany during World War II. PVC and other rigid pipes can be threaded and joined by threaded fittings [33].

In the 1970s crosslinked PE pipes, which are flexible and are lightweight have become widespread in sanitary installations. They have long-term heat resistance up to 95 °C and can also be used for hot water and under floor heating pipes [17].

Nowadays pipes are the invisible arteries of modern life: for fresh water, for drainage and sewage, for the gas supply, and increasingly as conduits for electrical and fibre optic cables, for such things as power supply, television channels and motorway signalling.

The total usage for pipes in Western Europe is around 2 million tonnes annually. At least 70% of it is PVC, the other main materials being HDPE and LDPE. Potable water pipes are usually made from PE [34].

Many other types of plastics have been approved for use with potable water, for example, PP, PA, PC, polybutylene, PES and PU.

2.1.1.8 Barrier Films

In the past, for the building envelope, paper or asphalt impregnated paper were used as a moisture vapour barrier. Today many polymers such as polyolefins (PE, PP), PVC, aliphatic polyamides, PET, PC, and others are used as protective barrier films against the mass transport of small molecules of gases, vapours and liquids. The barrier properties depend on the polymer characteristics such as solubility, diffusion, permeability, the nature of the fluid, temperature, and other factors.

2.1.1.9 Composites

The construction industry is using various kinds of composite materials such as: fibre reinforced plastics (FRP), polymer concrete, polymer-asphalt, fibre reinforced polymer concrete, and so on.

It is considered that the late 1930s and early 1940s marked the beginning of the age of designed materials, taking into account that the production of glass fibres was patented by Slayter and Thomas only in the 1930s [35, 36].

The main growth in interest and technology of the glass fibre-uPES composites in the building and construction industry was in the 1960s. Two sophisticated glass fibre reinforced plastic (GFRP) structures have played a major role in the development of these materials in construction; these are the dome structure erected in 1968 in Benghazi and the roof structure at Dubai Airport built in 1972. During the 1970s and 1980s GFRP was used for other prestigious buildings. In the early 1990s, the Neste Corporation (Finland) designed and constructed an experimental house as a test-bed for polymer-based construction materials. Of the materials used, 75% were manufactured from polymers and composites, showing that these materials can achieve results that are competitive with traditional materials and are aesthetically, functionally and technically sound [37].

In the period 1980-1990 there were major advancements in the evolution of composite materials technology. New developments in polymer resin formulations, fibre reinforcements, and processing technology led to increasing use of advanced composite materials in many areas.

In the early 1990s, FRP was developed in Japan to overcome the corrosion problems inherent in conventional steel rebar. This new rebar has been used for 10 years in non-structural applications. Structural use, however, has been slow to catch on because of a lack of design guidelines.

The earliest indication of the use of polymers in concrete was apparently in 1909, in USA when a patent for such use was granted to Baekeland and in 1922 in France and in 1923 in UK [38]. Polymers can be added by three different methods into normal concrete, leading to: polymer impregnated concrete (PIC), polymer modified cement concrete (PCC) and polymer concrete.

Polymers added in the form of fibres are now replacing the asbestos reinforced Portland cement that appeared in the mid-1980s. The fibres commonly used today besides steel and glass are PP and PA. A variety of other synthetic fibres can be used including PE, PES, aramid and carbon [39].

Polymer modified asphalt originated in Europe in the early 1960s. Atactic PP is still used today in asphalt compositions mainly in Europe, Mexico and Asia. A PP copolymer containing 2-10% ethylene is more popular in USA. Thermoplastic block copolymers with styrene end blocks or with a diene midblock like S-B-S and styrene-isoprene-styrene (SIS) and their hydrogenated versions are common modifiers for asphalt [40].

2.2 Use of Plastics and Rubbers in Construction: Current Status and Trends for the Future

The building and construction sector is the second largest user of plastics after packaging (in 1999, 18% of the total plastics consumption was from the construction sector which totalled over 6 million tonnes in the EU alone – this figure is above 20% today). Of the total amount of plastics used in construction, PVC has the largest share (55%), followed by PS (15%), polyolefins (15%), PU (8%) and others (7%). The use of plastics in the building and construction sector has a wide range of applications, from structural to cosmetic (or protective) and it is expected to grow even more in the years to come due mainly to the increased emphasis on energy efficiency in buildings [41]. The construction market in the EU is worth about 400 billion pounds sterling representing 8.5% of gross domestic product (GDP) (which is similar for the gross total but a lower share of GDP for both Japan and USA) [22].

Natural polymers have been used in construction in the form of wood and plant by-products in the past. The cost of some traditional construction materials, i.e., wood, are increasing steadily, which means that plastic building products are becoming a lower cost option with each day that passes. In addition, plastics have excellent strength to weight ratios, (i.e., expanded polystyrene (EPS) combines extreme lightness with a capability of withstanding high loads), their environmental resistances are exceptional, they provide more flexibility in design as well as huge benefits to builders, to designers and home owners.

Plastics materials over-simplify construction methods, in general, by reducing the amount of work necessary on site and usually less skill is needed for their application. They can be used successfully in buildings from the top (roof) of the house to the bottom (flooring) and even below (pipes); from exteriors (PVC cladding and exterior paints) to interior walls (wall partitions, wallpapers and paints). The first use of plastics in construction market was some 40 years ago, mainly being used as substitutes of some of the traditional materials. However, today, they are also being used in much more sophisticated applications in construction.

The use of FRP composite materials directly in bridge applications is gaining importance in recent years. FRP have advantages such as high strength/low weight ratio and corrosion

resistance that makes them good candidates for use in bridge construction and retrofits, in addition to some long-term economic advantages by reduced maintenance and labour costs. The University of Missouri – Rolla (UMR) designed and built an all-composite smart plastic bridge that is installed at the UMR campus, which is composed of carbon fibre reinforced pultruded tubes in the matrix of vinyl ester resin. The smart composite bridge has fibre optic sensors built into the structure. This application proved that all-composite bridge decks (made of pultruded glass and carbon tubes) can be a suitable replacement for bridges made of conventional materials.

FRP applications in structural rehabilitation, such as, column strengthening and seismic retrofitting by using FRP wraps, beam strengthening with bonded FRP wraps and prestressed laminates, as well as its applications to masonry and other structures are the focus of recent innovative work and these applications are expected to increase during the years to come [42, 43, 44]. The typical way to support cracked piers, columns and supports is simply to wind composite filaments around them. There is also the need for repair and retrofitting/rehabilitation in time as any infrastructure gets older. Nearly half of the 570,000 highway bridges in USA (that were built some 40 to 50 years ago) are reported as 'structurally deficient or functionally obsolete' [45], and need trillions of dollars for rehabilitation. In the Alberta province of Canada, almost 5,000 bridges were found deficient in shear strength, which could lead to a very dramatic type of failure. Examples like these can be easily found worldwide. All of these problems can and will be solved through the use of plastics composite materials, economically and quickly; sometimes by applying paper-thin graphite epoxy patches, a process which requires a minimum amount of demolition work before repair begins, hence, without rerouting traffic much during the process. Innovative composite bridge deck applications utilising glass or carbon fibres are increasing and will be a very productive area in the future. Currently, retrofits to reinforce substandard structures have a huge potential and their use is increasing.

In addition to their applications for repair and rehabilitation of damaged bridge decks in the form of durable and fast curing materials, plastic composites provide non-penetrating non-skid overlays and they are used heavily in a number of public-related projects, such as in the Channel Tunnel (1990s) and in the construction of stadia at the last Olympics in Australia.

All plastic composite materials are already used in some challenging civil engineering applications, such as, in a composite footbridge (Aberfeldy, Scotland, UK; 1992) and road bridges (Stonehouse, Gloucestershire, UK; 1994).

The 40 metre long and 3 metre wide all glass fibre reinforced plastic (GFRP) composite bridge to connect Scandinavia to the mainland Europe has just been completed in Denmark. The bridge weighs only 10 tons, just half the weight of a similar steel construction, and is expected to require only cosmetic maintenance throughout its life.

Polymers, after their combination with fibres to form special composites produces some materials with enhanced properties, enabling them to be used as structural members and units, competing with metals. The use of polymeric fibres in concrete to replace steel frame (as composite rebars) has many advantages which has been in use for a long time with an ever increasing trend in use, if the material costs involved are decreased in the future, as expected. However, proper materials characterisation in addition to development of new standard test methods still appear to be the immediate needs to be fulfilled in the near future.

There is a growing interest in the application of plastic composite structures more and more in construction, and a pan-European project funded under the Eureka scheme *(Eurocomp)* has the aim of designing the lacking criteria and specifications in structural design of polymer composites.

A carbon fibre composite blanket was used as a vibration damping stabiliser for bridge columns, seismic retrofits and structural reinforcements, while seismic bearings have long been applied to the base to increase the flexibility of the building (laminates made of natural and chloroprene rubber or high damping PU elastomer), and are used successfully for earthquake isolation. Most of the buildings in Japan and in certain parts of USA (California) are already (and in increasing proportions, will be) protected by such isolators.

Construction activities with building in recent years are mostly for both new residential and related repair/maintenance applications for the old, and these are much higher than for their civil engineering and non-residential uses, especially in the EU. There is a very big increasing trend in window and door applications in these countries (and, in addition, especially in China) and for this, PVC is expected to be the dominating plastic. After the first applications of smart windows in glazing, it is expected that the demand for this will be more towards the use of PC, rather than acrylics.

Insulation, mostly of heat, is expected to centre mostly on EPS in the near future, at least for general heat insulation applications. The problems associated with new blowing agents, (i.e., thermal inefficiencies involved for new blowing agents of PU) are expected to cause PUF use to decrease in general, except in flooring and roofing applications. Plastic fibre insulation, preferably produced from plastic wastes, is showing a big potential for their future use as insulators.

For flexible sheeting, as single ply roofing use, PVC and ethylene-propylene-diene monomer (EPDM) are expected to be the main polymers used. For wall and floor coverings PVC is still expected to continue to dominate the construction market. PVC will be the main plastic used for pipe and conduit, wire and cable, profiles and flooring applications, while EPS will be mostly used in insulation.

All-plastic (or most-plastic) 'concept' houses have been on show for a long time as mentioned in the previous section (such as Monsanto's '*House of the Future*', DuPont's '*Signature Place*' and the four storey GE Plastics' '*Living Environments House*', all in the USA, '*Futuro*', and '*Nestehous*' in Finland (the latter from Neste); where a large proportion of plastics are used with the most up-to-date applications of the time. In Nestehous, plastics account for 75% by volume of the materials used, where PP fibres reinforced concrete rebars are applied as the main load bearing units. The Nestehous features see-through 'a-Si modules' as window glass and crystal-silicon sun shades on the south facade to reduce summer cooling loads. The International Institute of Polymer Arts and Techniques (IIATP) of France built a plastic demonstration house (Milon House) with self-darkening windows and carbon/glass fibre (GF) composite frames, polyester amide doors, melamine walls, epoxy seals and transparent floors, with a very light triangular shaped textile/GFRP composite roof.

In recent years, better construction methods and products have been developed, although related technology still mostly depends on traditional labour intensive, on site-based work. However, there are also sophisticated technologies applied, such as, *intelligent (smart)* material applications, as well as, the prefabrication of sub-components such as (light) building frame members and modules. Earlier, in GE Plastics '*Concept House*', windows were prepared from two layers of PC sheets laminated by using a liquid crystal polyester film, which can change from clear to translucent via a switch hence natural daylight control can be explored easily. In the same house, voice-activated mini-blinds in living rooms regulates the amount of light as well, and there is a *health pad* in the bathroom to give readouts of the pulse rate, blood pressure, and weight, with the touch of a finger; and there is a voice activated computer on the top floor. There are also the following conceptual visions to consider: foam floor tiles are used (that form a grid to define the position of piping in the house), flexible quick-connect plumbing and a toilet system that incorporates a mulching unit are designed (to preprocess wastes, allowing much smaller waste pipes and reducing water volume) and there is the total environment control unit in the house (to combine new ideas in heat exchangers, reverse osmosis water purification, and heat distribution). Today, electronic control and communication systems are providing a basis for intelligent buildings. In fact, BASF developed a smart material that provides shade and overheating from incident solar rays; this will certainly be used for shutters and blinds as well as classical outdoor functional cladding in houses, panels in greenhouses and conservatories. The same company developed another smart system by using hydrogels that has thermotropic properties (changes in properties by heat), that is being used already to cool the company's exterior solar heating system where excess heat generation in summer is blocked effectively.

'The MIT Home of the Future Consortium', in its recent form 'Open Source Building Alliance', is working on a project (project House-n, the 'n' being scientific shorthand for

'variable') to prefabricate (plastic) smart houses most economically. The heart of this project is a chassis with an infill of cheap sensing devices like LED, speakers, displays, automatic lighting, heat sensors, and miniature cameras that can be plugged in at any point and upgraded; the network being self-configuring. The floors, the walls and the ceilings are all made of plastics in this design. Furnishings and equipment, as well as the house itself, are almost 100% synthetic.

A 'smart brick' concept was developed recently by scientists at the University of Illinois at Urbana-Champaign, Center for Nanoscale Science and Technology; that can be used to monitor a building's health, and hence can help to prevent disasters. The system, combined sensor fusion, signal processing, wireless technology and basic construction

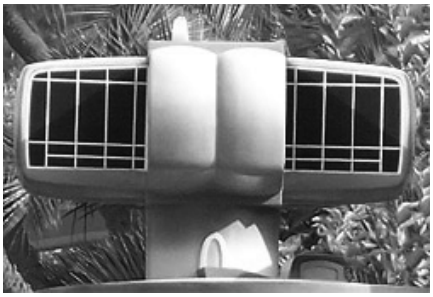

Figure 2.1 Monsanto House (1957-1967) at Disneyland, then at MIT, USA; all plastic; with ultrasonic dishwashers, foam-backed plastic floor coverings, atomic food preservation and plastic sinks with adjustable heights. Its demolition took a long time (two weeks) with a crew of several men than normal planned duration (one-day).

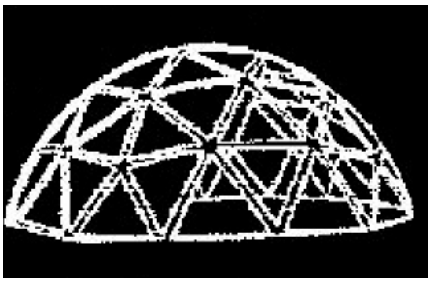

Figure 2.2 Computer controlled geodesic 'Dome Home' of J. Noel Pigout (to achieve energy efficiency by opening and folding in like a flower, closing up when temperature is too high or low and turning its back away from or towards the sun) (2001, Paris Fair),

material into a multi-modal sensor package that can report building conditions to a remote operator. The prototype has a thermistor, two-axis accelerometer, multiplexer, transmitter, antenna and battery hidden inside a brick, or, inside laminated beams, or other building materials. Built into a wall, the system can monitor a building's temperature, vibration and movement.

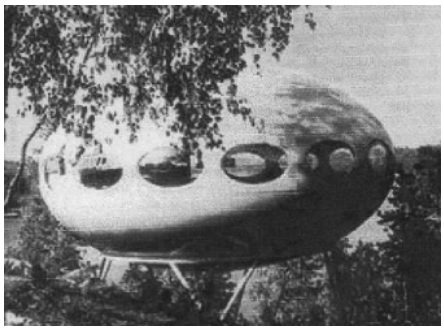

Figure 2.3 'Futuro' House (1968/2002) of Matti Suuronen design, from FRP polyester composite.

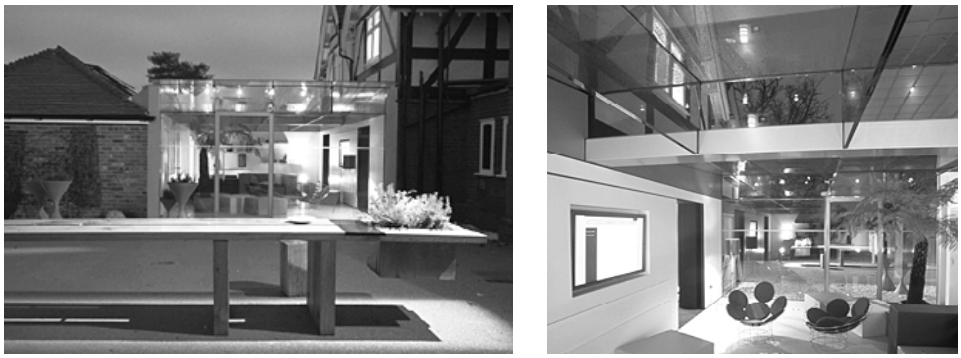

Figure 2.4 'Orange at Home' House (2001), an average Hertfordshire house is turned into a remote-controlled show home (UK). The house is powered partly by solar panels on the roof and is equipped with energy-saving innovations, such as, a hot-air recovery system that draws warm air from the kitchen and bathroom to heat the cooler rooms. Security is totally automated, and the front door can be opened with a mobile phone, room temperature can be set by yelling at the walls.

'NanoHouse Initiative' is a model house developed by the Commonwealth Scientific & Industrial Research Organisation (CSIRO) and the University of Technology Sydney (UTS) which shows how new materials, products and processes that are emerging from plastics and nanotechnology research and development might be applied to our living environment. As is known, nanotechnology is the design, fabrication, and characterisation of functional objects having dimensions at the nanometer (one billionth of a metre) length scale. The principles upon which NanoHouse is based are energy efficiency, sustainability, and mass customisation. The NanoHouse has a radiative cooling paint as the outer surface of some of the roofing material. A metal roof coated with this paint becomes a cooling element in a building rather than a source of unwanted heat gain (new paint additives that mean dark surfaces stay relatively cool, and light surfaces can absorb heat). Other features are self-cleaning glass (multifunctional windows), cold lighting systems and the dye solar cell – a photovoltaic cell based on titanium dioxide rather than silicon. Nanotechnology can also be applied to our living environment by embedded, distributed sensing systems that involve implanting tiny sensors (temperature, air quality, stress) in building materials. Using such systems we can get 'smart spaces' that use technology that can sense and act, communicate, reason, and interact with us to make our living and working environment more comfortable. The architectural model of the house is the first stage of the concept, with the creators planning a full size version in the future.

In Chapter 6 (Section 6.8, smart materials and structures), additional information is provided on the subject.

Future trends in the EU for plastics construction materials is increased use of plastics piping in sewage transport.

PU and PIR rigid foams account most for general and phenolics for indoors applications, this trend is expected to be the same for the future.

The 'three-litre house' that consumes an equivalent of only three litres of heating oil per square meter of living space was realised by BASF and is on the market. If compared with the 'unmodernised' building with 2,000 litres of oil consumption (costing approximately 700 EUR) with an estimated 6 tons of carbon dioxide emission for a 100 m^2 house, the three litre house will need 300 litres (costing 100 EUR) of oil producing 0.9 tons of carbon dioxide (both in oil consumption hence cost of heating, and in carbon dioxide emissions, there are considerable decreases expected per year) [46].

Processing wood plastic composites (WPC) into profiles by extrusion for building and construction applications is one of the most exciting businesses of recent years. Growth observed is such that WPC applications are already very high (at least 30% a year in

Europe), and new applications will continue to be found in the future. This market is more active in North America, which based largely on the success of WPC decking applications and is expected to more than double by the year 2006; however potential in Europe is also vast and growing quickly. In Europe, wood plastic composite products are mainly used in a wide range of applications, ranging from basic solid extrusions to engineered profiles in high performance interior applications; including window profiles, garden furniture, fencing, doors, cladding, crates, roofline products, and decking. Shorter cycle times are possible when injection moulding WPC and there are environmental benefits to be gained when WPC are produced from waste wood and recycled plastics, another very attractive consideration for using WPC systems, which certainly helps it to compete favourably with other plastics. In Japan, WPC are used for a high quality finish for interior applications.

There are studies to develop better and much safer insulating products for the future homes, such as aerogels, powder-filled/evacuated/vacuum insulation panels, and phase change materials.

Aerogels are one of the strongest, lightest and yet transparent (although non-polymeric) building products with 99% of empty volume, typically produced from silicone or carbon; with equivalent thermal insulating efficiency equal to 10-20 glass window panes [47].

Insulation panels use the Dewar's principle [48] which uses reflective outer layers and encaged stagnant insulating media in between, which is the most effective way of heat insulation.

Phase change materials, which are non-polymeric as well, can store and release energy by changing phases when used for electronics cooling, etc., by allowing substantial thermal storage to become part of the building's structure without effecting the temperature of the room envelope, hence daily indoors room temperature fluctuations are smoothed. Another phase change material application was developed recently as a specific attic insulation which absorbs heat during the daytime and releases it at night, where the attic is hermetically sealed with polymeric foams [49].

The future will certainly see the applications of a wide variety of new and improved materials in construction. There are improvements and tailored properties through process simulation and modelling for functionally graded materials, layered structures, nano-structured multifunctional materials for ultra-lightweight structures, and 'smart' materials. Use of digital technology already led to a number of smart housing innovations: voice-activated appliances, homes that set their own thermostats and recognise their owners by 'dog tags' or badges (used for unlocking doors, turning on lights, etc). Microsoft's Bill Gates recently made an alliance with Samsung to develop home technologies to produce

an 'entire ecosystem of personal computers, digital devices, intelligent home appliances... transform[ing] average households into next-generation digital homes'. In the current Gates estate, there are touch-sensitive pads to control lighting, music, and climate in each room, and automatic setting of lights and of heating the floors throughout the house (and the driveway).

The Smart home approach is the future trend for homes with a lot of home automation and smart concept applications. In all of these, the possibility to create a home and environment that is aware of its occupants and activities to provide services to enhance the quality of life or to help residents to maintain independence as they age. The following examples are just a random collection of them.

Several years ago 3M developed a paper-thin, electrically sensitive Privacy Film, based on patents held by Kent State University and Raychem Corporation. Between two sheets of this film, a layer of liquid crystal was put and all are held between panes of glass to produce the Privacy Glass (Electrically switchable 'smart' windows). When electricity is applied to this system, the liquid crystals line up and the foggy material becomes clear, when the current is withdrawn, it becomes opaque again.

Now there are smart windows that sense climatic changes or that go from opaque to clear, on their own.

Mood paint has a thermochromic carbon-based pigment, and fades as the temperature rises and brightens as it cools (NASA developed this paint as a coating that would warn scientists when a machine was overheating). Mood paint if used as an exterior house paint would darken and absorb heat from sunlight during cooler seasons. Jürgen Mayer Hermann, a German artist, created his housewarming installation by using mood paint indoors and showed that when the wall is touched, the colour temporarily fades, leaving a sort of negative shadow. This will probably be the 'interactive' wallpaper that can be altered to suit the mood.

Low-energy interior wall and ceiling paints can be accomplished by use of *radiance paint* that reflects radiant heat energy back into a room in the winter and reflects radiant heat away in the summer (which is applied in space shuttles to let astronauts stay comfortable) with which the estimated energy saving in radiance-painted rooms will be 5 to 15%. Similarly, furniture can be made out of smart materials that can change colour and/or even conform to shape.

Smart wall and the smart concrete concept was created by Deborah Chung, from the State University of New York at Buffalo, by embedding electronic properties into materials so that surfaces are able to store electricity and have the intelligence to measure and control climate, as well as to scale the weights above them.

For Smart walls, carbon fibres bound by an epoxy matrix are used that act as a structural material and as a semiconductor. It is less expensive, less fragile, and easier to produce than silicon circuitry, structural electronics will allow walls to store energy and act as control circuitry.

For smart concretes, ordinary concrete reinforced with short carbon fibres are used which can conduct electricity and give the surfacing mixture measurable electrical resistivities to function as a 'scale' that can detect the weight passing over it by following the change in the amount of contacts between the carbon fibres, as it alters, the resistance of the mix is affected. The Smart concrete concept is expected to be used in highway engineering as well as indoors, (i.e., as smart flooring in bathrooms in place of bathroom scales) [50].

Carbon fibres can also be used to create other types of smart concretes that can sense and report structural damages. Sandia is exploring candidate smart materials that can be attached to or embedded into structural systems to enable the structure to sense disturbances, process the information and through commands to actuators, and to accomplish some beneficial reaction such as vibration control.

Recently, the nano concept is included in construction as well and it is applied to a model 'nanohouse', developed by the CSIRO, Australia and the University of Technology Sydney (UTS); showing how new materials, products and processes that are emerging from nanotechnology research and development can be applied to our living environment (on energy efficiency, sustainability, and mass customisation) [57]. The NanoHouse has a radiative cooling paint as the outer surface of some of the roofing material. A metal roof coated with this paint becomes a cooling element in a building (rather than a source of unwanted heat gain). Other features of the nano house are self-cleaning glasses, cold lighting systems and the dye solar cell - a photovoltaic cell based on titanium dioxide rather than silicon.

Smart materials and structures are presented in more detail in Chapter 6 (in Section 6.8).

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3 The Use of Plastics in Building Construction

Güneri Akovali, Dorel Feldman and Bireswar Banerjee

3.1 Introduction

Building means any structure that is used (or intended to be used) for supporting occupancy or sheltering. Building construction is currently one of the largest industries worldwide, i.e., new construction in US was approximately 620 billion US$ [1], and with renovation, maintenance and repair added, the total volume of construction was about 1000 billion US$ (during 1997-1998), corresponding to 12.3% of the GDP. In the EU, the construction market was about 400 billion pounds in size (in 1997) which grows about 2-3% per year [2].

Within building construction, residential construction has the highest share in general (approximately 40%), followed by commercial institutions (30%), public works (20%) and industrial constructions (10%).

There are a number of different materials involved in the building and construction sector, beginning with cement (used to produce concrete) and lumber, which are the classic and common materials. There is also a variety of novel plastics materials being used in the same sector, which are not that old, and their use is ever increasing and replacing the conventional ones. 'Lumber' and 'composites of various ligno-cellulosic fibres with plastics' are being used in large proportions in construction.

Plastics have a wide range of applications in the building industry, and this sector is the second largest user of plastics. These applications range from non-structural to structural uses, inside and outside of the house, because of the fact that plastics materials have several advantages, such as, they are light, economical, durable, have high performance characteristics, are easily handled and processed and have aesthetic properties. In the case of fibre reinforced plastics (FRP), high strengths are combined with low weights. If glass, carbon or aramid fibres are bound by polyester, epoxy or vinyl ester resins in a FRP structure (say in the form of a rod with a nominal diameter of 7.5 mm with 60,000 fibres developed for use in building construction and as a tensioning element) has at least the same longitudinal tensile strength that the best pre-stressed steel has. Since polymer composites are light, using them can minimise the destruction and damage due to the deadly falling elements during an earthquake or tornado.

Although there is still a rather slow pace of acceptance of plastics and its composites in construction mainly due to the general lack of knowledge of the properties and applicability of these new materials as well as lack of availability of related building codes and standards, they are being recognised, appreciated and applied more and more every day [3].

Polymer structures are used in construction as either (i) structural or (ii) non-structural elements, as well as (iii) cosmetic (or protective) and repair elements. Hence a classification for their use in construction can be done by using these criteria. Within these, their non-structural use is more common than their use with other applications.

However, it is also possible to make a different classification for use of polymers in construction, by considering:

(a) polymers that are used in the building envelope (which includes all building components that separate the indoor from the outdoor, such as, exterior walls, foundations, roof, windows and doors – all provide a thermal shell), and

(b) polymers that are used in other applications.

Both of these classifications will be used to some extent, interchangeably, in the following parts.

3.2 Structural Applications of Polymers in Building Construction

Structural applications are such that they require proper mechanical performance (strength, stiffness, vibration damping ability) in the material, which may or may not bear the load in the structure. Structural components should withstand 'live' loads (such as: people, wind, etc.), as well as the 'dead' loads (the weight of the structure), which can be (a) 'load- bearing' walls, (b) columns and beams, and (c) bracing: in frame construction, or 'shear walls'.

Load-bearing structural applications of polymers are mostly FRP or their advanced composites, where there are high strengths and low densities involved. After their development and use mainly for military and aerospace applications during and after 1940s, these materials are being used in a number of different structural applications, including load bearing sandwich panel (SWP) and infill panels [4], rebars, complete stand alone structures where FRP units are connected together and the shape provides the rigidity needed.

For primary structural applications, which are load bearing: firstly the strength of the material should be able to support at least in-plane loads, with proper stiffnesses (if bending and shear forces are involved), and mechanical property requirements are

critical. Since under the design loads, the shape of the structure should not deform, materials with high strengths are usually selected in construction. It should be remembered that, the failure of primary structural material can cause the complete collapse of the system, which is not replaceable. Beams and columns are known as the main primary load carrying members in buildings, which are with much larger lengths than their depth or widths, with symmetrical cross sections, designed to bend in this plane of symmetry which is also the plane of highest strength and stiffness coinciding with the plane of applied loads. Beams (and composite beams) are fabricated beginning from metal, reinforced/prestressed/polymer fibre reinforced concrete (rebars) and FRP materials. Load bearing wall units and sandwich type beams, surfaced with pultruded FR polyester profiles containing EPS cores (with reinforcement bars and concrete casting) is applied successfully, i.e., in the Neste model house.

In general, composite skeletal systems manufactured by pultrusion have extremely high axial and flexural strengths and relatively low transverse strengths, and their hoop strengths can be improved by incorporating hooped strands along a reinforcement core. Continuous fibre mats are also frequently used to improve the transverse strengths of pultruded structures. There are different methods used for jointing of skeletal composite structures [5].

Rebars are polymer fibre reinforced-concrete composites, and they are used as primary structures. It is estimated that replacement of steel reinforcing bars by non-corrosive polymer fibres, i.e., by Kevlar or carbon fibres (which gives rise to Kevlar or C-composite bars) for concrete structures produces structures with one-quarter the weight and twice the tensile strength of the steel bar. It is known that, corrosion of steel reinforcement from carbonation or chloride attack can lead to loss of the structural integrity of concrete structures, and such a danger is non-existent for rebars. Thermal expansion coefficient (TEC) values of these fibres are closer to concrete than that of steel, which provides an another advantage; and they have the same surface deformation patterns as the steel bars. In addition, they can provide more economy than epoxy-coated steel bars.

Composite rebars can be prepared by use of various polymeric fibres, such as, carbon fibre, E-glass fibre and Kevlar/aramid fibre. For high modulus requirements, hybrids of carbon-glass and aramid fibres are applied. C-composite rebars are used preferentially in places where non-corroding and non-magnetic structures are needed (in sea walls, hospital MRI room walls, reactor pads, roofs of chemical plants, transmission towers, military structures, in areas where EM neutrality is needed, and applications in other salt water areas, bridges, etc.). Composite rebars with carbon fibres can also be used to check the self-diagnosis of the structure, by following the changes of electrical resistance of the structure.

Composite rebars are applied either as continuous pultruded rods or as structural profiles. Glass fibres, although they have lower moduli values (some 20% of that of steel), can still provide high tensile strengths (approximately four times higher than steel). However, it should always be remembered that the modulus and the strength values in polymer composites are also highly dependent on the volume fraction and orientation of the fibres, hence the orthotropy of the material must be considered in the design and application of the composite structures at all times.

In addition, since defining the material's criteria for design of polymer composites is more complicated than for other conventional structural materials like steel, concrete and aluminium, and because they depend on factors such as the details of stress-strain-strength behaviour, as well as on the changes in these properties with time-temperature-processing conditions and stress environment, (i.e., creep); it is suggested that the 'limit state design principle' is employed [6], which provides the basic tool for determining the limits of their application as a structural material.

Nevertheless, FRP fibres are better candidates for the pre-stressing and post-tensioning tendons in concrete structures than steel [7], and more than 15% of glass fibres produced are already being used by the building and construction industry [8, 9].

The secondary structural materials are materials that if the structure fails can only cause local damage that can be repaired, such as secondary wall panels for a steel framed building in a modular construction. These panels, which are aesthetically pleasing, are light to handle and are low in maintenance, are SWP with FRP or rigid metallic skins on the face and have a polymeric foam core, usually of EPS or PU. The load on these panels is mainly the pressure induced by wind.

The complete 2,200 m^2 wall façade of Dubai airport is fabricated from FRP and it comprises architectural components (single and double arches) and images.

Structural bearings are widely used for bridges and expansion joints. Isolation of buildings from ground or structure-bourne vibrations (as well as protecting the building from damage of earthquakes) by use of secondary structural rubber bearings, even rubber blocks, has been used for a long time [10-14].

3.2.1 Sandwich Panels (SWP) and Sandwich Panel Applications in Housing Construction

SWP [15] are layered structures with thin, two high modulus (metallic, concrete or polymeric) facings adhered to a lightweight core of foam or honeycomb. They can be

transparent (where the core is GRP honeycomb and with layers of transparent rigid polymers) or non-transparent (as is generally the case).

SWP use in construction dates back to the end of World War II where they were used for for cold stores and freezers. And in recent decades, it is applied in a number of different building applications. It offers an alternative to 'solid construction' methods with its favourable economy, lightness and function; the high modulus facings (usually metallic) and the core, (i.e., PU rigid foam) possess an ideal combination of physical, mechanical and structural properties. SWP, currently has a share of 12.1% of construction and most of this is for warehouse construction and industrial buildings. SWP application for domestic buildings is rather small currently (approximately 5%), and it is increasing.

When use of SWP by the construction element is considered, most of it is applied externally (as external walls and facades, 56%), followed by roof insulation (30%) and for ceilings, internal and partition walls (14%). SWP can also be installed as wall panels with integrated windows, for various indoors separations, as acoustic roof panels and as construction accessories (variable connecting SWP panels to connect individual wall and roof panels) and in prefabricated housing and shelters.

Most of SWP are used with steel or reinforced concrete as supporting structures. In SWP construction, there are practically no restrictions on building dimensions.

When used as an external wall element, it is calculated that to provide the same heat insulation level, a SWP with 80 mm rigid PU core insulation can replace 385 mm of conventional masonry wall. When conventional 24 cm thick masonry with 2 cm resin plaster wall is compared with 80 mm SWP wall, the latter would need 6 times less heating oil per m^2 of external wall. SWP use effectively lowers heat transmission losses resulting from thermal bridges. Although degree of elimination of noise is known to improve with increase of mass in general, lightweight SWP can still help to eliminate noise effectively through its 'high acoustic damping factor'.

In SWP, the shearing and tension-resistant components of the thin facing units, along with the thick core, creates a new structural material with completely different load bearing behaviour: the three layer sandwich has a synergy in bending and torsional resistances; both are much greater than the sum of the individual components. The whole shear force is completely taken up by the core, and the deformation stiffness is associated with the shear rigidity of the rigid PU core. Because of their high stiffness, they are self-supporting and have excellent load bearing properties, despite their light weight. They are usually fastened to an open framework as a transverse web to carry shear loading (and are used occasionally as a primary structural member). They can be successfully used as a building envelope as well as the (secondary) load bearing components (wall

and roof components). For these load bearing applications, a minimum density of 36 kg/m^3 PU rigid foam is needed in the core. Recently complete SWP panel systems for roof and wall cladding were developed and used. In one of these, on the curved facade, 60 mm thick and 900 mm wide, SWP are installed successfully with external triple layer coating (waste disposal plant, ROTEB, in Rotterdam, The Netherlands - this incinerator burns 380.000 tons of domestic waste annually to produce 190 million KWh of electricity).

SWP store little heat (with no heat radiation) and hence they provide excellent thermal comfort.

The main advantages of SWP are summarised, and they mainly provide the following in construction:

(a) accelerated building erection, and cost savings in construction and in energy,

(b) simplified planning and use of SPW gives a number of different architectural design possibilities,

(c) SPW provide physical construction quality and a substantial energy saving and space climate

(d) they offer flexible rebuilding and extension possibilities.

Figure 3.1 presents a general type of SPW with its core replaced by a honeycomb structure.

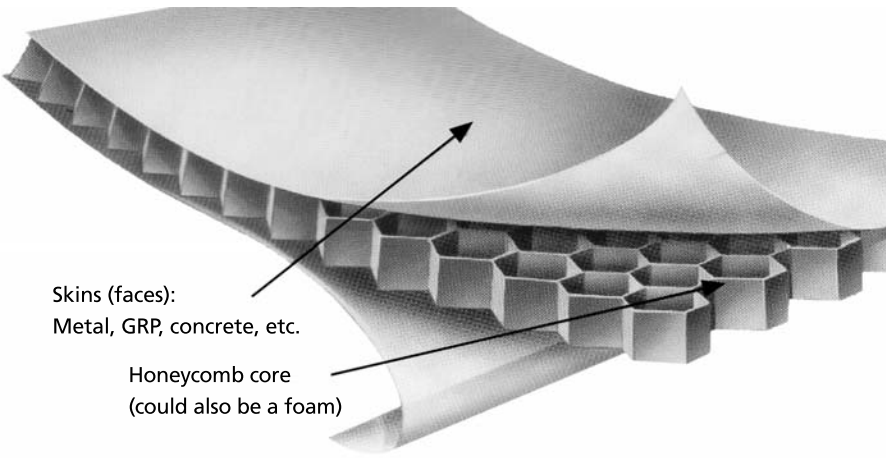


Figure 3.1 A typical SWP (with a honeycomb core)

3.2.2 All-Composites Housing

There are several buildings that have already been constructed completely from polymeric composite materials within the last decade [16]. Faber Maunsel Structural Plastics (Beckenham, UK) is one of the companies who have been involved. They built several prototype single and two storey buildings in the 1990s with the Advanced Composite Construction System (ACCS) [17], consisting of pultruded E-glass/isopolyester multicelled modules with interlocking joints connected for walls, floor and roof assemblies which are used to construct complete monocoque buildings without need of additional framework. This house is claimed to shelter from two to 500 people, is highly durable and easy-to assemble. FRP composite structures are also proposed as a possible earthquake-proof construction method, with buildings assembled from interlocking FRP panels held together by adhesives and a mechanical fastening system [18, 19].

A large scale, multi-cellular reinforced plastic (RP) polymeric structure was constructed at Weston, USA, for a multi-purpose facility use of Division of Highways, in 1995 [20], where the entire walls are constructed with RP multi-cellular panels made of E-glass fibres and polyester resin, and are connected with wide flanges.

In 2000, Goldsworthy & Associates, USA, showed that a three bedroom, two bath house can be assembled completely in four hours with unskilled labour. In the Goldsworthy Innovative Fabrication Technology (GIFT) housing project, pultruded structural insulated panels (SIP), of woven 0°/90° E-glass roving with phenolic resin over a proprietary material; along with novel snap-lock joining technology, were used. The modular composite house, which received the PATH award (Partnership for Advancing Technology in Housing), was mainly aimed at emergencies, as well as for housing in the Third World and developing countries.

In the same year, the Abersham Technology Group, UK, introduced their recyclable, all composite house, where no timber or steel was used at all, and wall and roof panels are of structural sandwich panel (SSWP) construction with skin laminates and core consisting of a blend of glass chopps or glass beads, respectively, and unsaturated polyester (UPE). An interconnected network of pultruded carbon/epoxy cables as solid rods were used through each wall and roof panel (to simulate rebars) and they were attached to the structural concrete slab foundation, and were additionally extended vertically from the foundation through the wall panels to the roof, creating a greater load resistance than the dead load of the concrete to provide greater resistance to hurricane winds and earthquake forces [16].

A new folding-house was also developed by Top Glass SpA, Italy, as a portable emergency all composite system.

Medabil (Brazil), patented all-vinyl houses as 'Casa Forte' (meaning strong house) and first group of plastics condominium, vinyl houses (the structure is made mostly of vinyl and vinyl profiles filled in with concrete and steel support) are being built by them in the city of Canoas with a total of 131 units each with 72 m^2, with a 30 year guarantee. It is further planned to have 3,000 houses on the same location soon, and this construction is approved for funding by CEF (Brazilian Federal Savings Bank) [21].

3.3 Secondary Structural and Non-Structural Applications of Polymers in Housing Construction

These are a number of *non-load bearing applications of polymers*, and their use is more common in housing construction. These non-load bearing secondary structural or non-structural applications can be categorised in four main areas:

(a) piping and conduit,

(b) cladding and profiles,

(c) insulation materials, and

(d) sealants, gaskets and seals.

In addition, there are other special non-structural applications of polymers in housing construction, such as, wallpapers, glazing, fencing, paints and coating, and so on.

Of these, pipe and conduit applications (which are mostly of PVC followed by PE) accounts for the highest use (35%) in building construction, followed by cladding and profile (mostly of PVC, 18%) and insulation (mostly from EPS and PU, 17%), by flooring (of PVC, 10%), wire and cable (PE and PVC, 8%), and film and sheeting (8%), applications [2, 22].

3.3.1 Piping, Electrical Cables, Wiring and Conduit Applications of Polymers in Housing Construction

3.3.1.1 Piping

Piping, which is defined as the arterial sanitation of houses is an important, functional part of buildings, used to deliver clean, potable water (for drinking and for other purposes) and gas, as well as to convey waste water away from buildings (for their treatment and subsequent reuse).

A variety of piping materials have been used in the past, (i.e., asbestos cement and ductile iron), and since the introduction of plastic pipes in the first half of the 20th century (first in Europe then in the USA), plastics piping materials, mostly of PVC and various grades of PE predominates the sector. In general, plastic pipe and fittings have temperature limitations as a disadvantage and there are also restrictions for their use at rather low pressures. However, plastic pipes offer higher resistance to environmental conditions (corrosion resistance) and have durability; they provide considerable reductions in weight, ease and economy of fabrication and installation, ease of repair and (relatively) low cost. Plastic pipes have a smoother bore than their metallic counterparts, hence flow rates can be increased and scale formation is reduced. Plastic pipes of small diameters are available in continuous lengths of up to 100 m (even up to 250 m in some cases), that help to reduce the number of joints and the number of potential leak points.

Within buildings, the push-fit waste systems have made plumbing much quicker, and also safer.

In addition, it is shown that, plastic pipes in the house and out (such as underground), all show good resiliency in the case of earthquakes that beats all other traditional materials available (Valencia Water Company, USA, the California private utility was able to compare the performance of three pipe materials – asbestos-cement, PVC and steel, during the catastrophic Northridge earthquake of January 1994, and found that PVC outperformed the others). Since the Kobe earthquake, which showed the structural weakness of traditional pipes, HDPE pipes are preferentially being used as gas pipes [2].

Plastic pipes are available in different lengths, diameters and pressure classes with a full complement of standard fittings, valves and couplings. They are compatible with other pipe materials and they can be specified for either new construction or for system upgrades. Plastic pipes can be repaired easily if for any reason they are damaged. On the other hand, traditional metallic and other pipe and tube installations can be sealed and/or repaired, (i.e., by spray coating of epoxy [2]) by use of polymeric materials.

The Association of Plastic Manufacturers' in Europe's (APME) report demonstrates that plastics' use in 'gas, sewage and water piping' has tripled in the EU between 1970 to 1995, rising from approximately 650 K to 1.9 M tonnes.

HDPE, PVC, acrylonitrile-butadine-styrene (ABS), PB and polypropylene (PP) pipes entered the market as 'solid walled, varying thickness' pipes of 'small and large diameters', however, PVC and PE pipes and fittings are more widely accepted and used in construction in water and gas piping, although they still are facing some competition from metallics, (i.e., copper, cast iron). In general, plastic pipes with diameters up to 30 cm are almost all made of PVC, (specifically, PVC-U). Chlorinated PVC (CPVC) and molecularly oriented PVC (MOPVC) are used for large diameter industrial pipes, where high corrosion resistance is required,

and for high pressure pipes, respectively. MOPVC are specially processed where fracture failures are ductile, and crack paths follow the laminar structure of the pipe circumferentially [2]. The lifetime of vinyl piping and fittings are estimated as 50 years.

For potable water, PE pipes are preferable. HDPE is mainly used for pressure water pipes (approximately 6.3 MPa) with both small and large diameters, while low density polyethylene (LDPE) pipes with small diameters are used for low water pressures (4 MPa). Use of medium density polyethylene (MDPE) and its blend with HDPE as pipes, for higher water pressures (8-10 MPa) and with better long-term performances in addition to higher flexibilities, are more recent. PE high pressure irrigation pipeline systems are commonly used. There are cases for the use of linear low density polyethylene (LLDPE) and its blends with MDPE in plastics piping. Usually blue grades of PE are for high pressure water delivery and underground potable water distribution, which enables the buried pipe to be immediately identified, orange/yellow for gas distribution (both with certain UV stabilisers) and carbon black grade is for (above ground) pressure waste water and gas pipes. If existing domestic supply pipes are corroded, the replacement (yellow) plastic pipe is threaded through the existing pipe. The plastic pipe placed beneath the ground surface (the underground pipeline used for transmission of water, gas, oil and other liquids) are sometimes called geopipes [23] and over 95% of natural gas transmission lines are made of HDPE geopipes.

FRP pipes prepared by use of GF reinforcements are usually the material of choice for transporting corrosive fluids and when external corrosive conditions exist, hence they are used mainly in industrial custom and commodity piping applications [24].

For hot water systems, (i.e., in underfloor heating systems and for hot water distribution), pipes are mainly polybutylene (PB), which can be used in systems with a continuous operating temperature of 82 °C and can survive short peak temperatures of up to about 110 °C, as well as crosslinked polyethylene (XLPE) with improved creep resistances, that can withstand operating temperatures for the same range as PB. The heat dispersion is optimised by these plastic piping systems by using the heat storing capacity of the floor.

3.3.1.2 Electrical Cables, Wiring and Conduits

It is estimated that about 5%t of the total value of a real estate belongs to electrical cables and wiring. Within the polymers used for electrical cables and wiring, PVC electrical products are the most durable that provide electrical and fire safety at low cost and contribute to the life safety in building design. PVC-U is inherently flame retardant, but PVC-P looses this property somewhat (because of the plasticisers used) and are used

with certain flame retardants added. New generation electrical wires are available with the second lining of a double layer of PVC providing higher insulation and higher resistance to bending, rolling and pressure. A slippery vinyl coating applied on the wire helps the instalment, (i.e., passage of wires through the conduits, etc.).

For plastic conduit systems, there are PVC-P, PU or Nylon for special flexible ones, and PP or PVC-U in most rigid nonmetallic conduit systems.

There are alternative cable types available with low-smoke, zero halogen (LSOH) characteristics, which are claimed to be safer and are being used in several underground railway systems in Europe and USA.

3.3.2 Cladding and Profile Applications of Polymers in Housing Construction

3.3.2.1 Cladding

In the construction sector, the use of 'easy-to install' materials are always preferred, and the coating of façades and application of sidings were always rather expensive and time consuming construction procedures. For this reason, until recently, residential exterior cladding was considered only as an option, and until the 1980s, aluminium (and wood) were predominant in this application. The recent large acceptance of plastics siding and accessories as an essential exterior element in housing construction is mainly due to the ease of their application and the favourable economy involved, in addition to the traditional or modern looks they provide, and their energy efficiency. In recent years, cladding and siding is the fastest growing segment in the construction sector and its use is expected to reach to 1.4 million tons by 2005 [22]. Currently, PVC siding has about 50% of the market share for exterior cladding products on residential and light commercial buildings. The popularity of use of PVC-U in cladding and accessories (soffit, fascia, etc.), which are provided in different colours and shades, (including the vertical/horizontal wood grains or in a smooth matte finish) is because of the durability, ease of maintenance, impact resistance, versatility and low installation cost. On new buildings particularly, PVC-U external panels, fascia and soft boards are frequently being used in place of traditional timber products.

Exterior normal size cladding is often prepared with either solid or foamed PVC-U (double skin or foam filled double skin) with the look, feel and workability of wood (they can be nailed, machined and cut like wood). However, during fixing of PVC-U cladding products, proper allowance must be made (approximately 2 mm per metre length between sections) for thermal expansion and contraction, to prevent buckling of the sheets due to the possible heating effect of sunlight, unlike their timber counterparts. With the double

skin cellular construction, sink or shrinkage marks are often seen running along the ribs. PVC-U claddings are light in weight, they have good resistances to rot and warp, they are inherently flame resistant, they are available in a variety of colours and finishes, and they do not need regular maintenance, (i.e., painting). PVC siding, usually in the form of a parallel bar coating fixed to profiles, is used for the covering of both residential and commercial facades and is an easy-to apply material.

PVC siding with parallel bar configuration is a very aesthetic, very easy finishing material to apply against block, brick, steel or wooden walls that do not require any painting or other maintenance. The bars are installed leaving a certain distance between them which is determined by the known regional climatic coefficients. It is self-extinguishing, highly resistant to traction, resistant to UV, air pollution and corrosive sea-air, and can conserve its characteristics up to 70 °C without showing any deformation.

Larger claddings are usually prepared from polyester based GFRP. There is also a trend for the use of cladding panels made of phenolics as their excellent flame resistances are considered, in particular for public structures (like railway - airport terminals, hospitals, and schools).

3.3.2.2 Profiles

Use of plastics materials in profiles in construction, mainly in fenestration applications such as windows and doors, which replaces the use of aluminium, wood or steel, gives rise to better energy efficiency, aesthetics, low maintenance and design flexibility, in addition to the economy. Introduction of new extrusion techniques in plastics processing have also helped to promote the use of plastics in profile applications. In the USA, demand for plastic windows and doors are expected to grow by more than 7% through 2007 (currently 2% of all window and door demand in USA in plastic) to give a market share of 6.2 billion US$ in the USA [25].

PVC-U has been in use for many years for the manufacture of window frames, particularly, for double glazed windows. There are substitutes, such as PP and styrenics (ABS with acrylonitrile-styrene-acrylonitrile (ASA) capstock) and wood composite alternatives, however, PVC is still the strongest and alternatives seem to complement it.

Several advantages of using plastics window frames are:

(a) their lower thermal conductivities compared to equivalent metal frames, which provides more effective thermal insulation helping to reduce condensation on the frame,

(b) they can be more easily assembled,

(c) they do not require regular maintenance, and do not need a wooden surround or a sub-frame (only for the larger frames, steel reinforcement is usually added for extra strength and security).

Plastic frames with low heat conductivities provide energy savings, stable fixation, durability and low service costs for a long time (average estimated usage time of a PVC frame is 40 years).

Extruded PVC prepared with a variety of different formulations and in different forms, including a wood-vinyl composite that is made of sawdust as well as a vinyl cellular foam that can be extruded into solid shapes, are all used in the production of a variety of window styles (traditional, single-double or triple hung windows, sliding windows etc.) [26]. Being inherently fire resistant, which can be enhanced with flame resistant additives whenever needed, and durable, PVC is the preferred and the leading material for frames in construction, since the production of first plastic window profiles in Germany after World War II from extruded frames of PVC. During the period of 1992 to 1998, PVC window applications grew by nearly 125%, in residential new construction and remodelling.

Fully reversible and enhanced security casement window systems and doors made by pultruded FRP were first introduced in UK with their low environmental impact, energy-saving abilities and design versatility.

A water tight seal of the frame to concrete and brickwork is usually done by bedding the frame in silicone rubber and by injecting a silicone rubber bead along all joints [27].

3.3.3 Insulation Applications of Polymers in Housing Construction

Insulation applications of polymers in construction, in general, can be one of the following three types:

(a) heat insulation,

(b) moisture insulation, and

(c) vibration and sound insulation.

3.3.3.1 Heat Insulation

There is transfer of heat (from hot to cold), whenever there are two areas of different temperatures, through either conduction, convection or radiation. In a house, heat

conduction occurs through the material it is made of, and convection is realised by currents of air within the house, attic and wall cavities. Heat energy may also be radiated across the air space and then it can be absorbed by an another body. Heat can also leave the home by air leaking in and out, i.e., through cracks, gaps or existing holes. Heat insulation materials are used to control the transfer of heat through the home's envelope. Insulation strength is rated in terms of R (the thermal resistance, in m^2K/W, indicates the ability of a particular thickness of a material to resist heat flow), the higher the value the better the insulation effectiveness. The R value depends primarily on structure of the material, as well as on its density, and on how and where the installation is made (whole wall thermal performance [28]). Thermal conductivity, k, with units of W/mK, is an another term used frequently, and it specifies the rate of heat transfer. A value of 1 for k meaning: 1 m^3 of material that transfers heat at a rate of 1 watt for every degree of temperature difference between opposite faces, eventually, the lower the value of k, the higher the insulating ability is. Thermal conductivities (k) are usually for heat transfer in any homogeneous material, whereas thermal resistance (R) is for a material or assembly of materials, (i.e., wall of a building), in such a way that overall thermal resistance of an assembly of materials can be found simply by adding individual R values. The reciprocal of R is known as the U (heat transfer coefficient or heat loss factor), with units of W/m^2K. U is similar to the k value, in that it measures the quantity of heat flowing through a 1 m^2 area during one hour when there is a hot-to-cold side temperature difference of 1 K. The lower the value of U, the better the insulation is. The U value is one of the most important criteria to judge the wall's ability to retain heat, and the statutory U value required for new buildings and extensions/refurbishments is 0.45 W/m^2K [29].

Basically there are four different types of heat insulation:

(a) blanket insulation (in batts or rolls),

(b) loose-fill (blown-in) or spray-applied insulation (with rock wool, fibre glass, cellulose or PU foam),

(c) rigid insulation (with extruded/expanded PS foam, PU foam, polyisocyanurate foam sheets),

(d) reflective systems (foil-faced systems, i.e., foil faced PE bubbles/plastic film etc).

Fibreglass (in batts, loose fill or fibre glass batts in sealed bag forms) and rock wool are two common (mineral) insulations that have been used since the 1950s, in addition to cellulose.

Air is known to be a good heat insulator, and when it is trapped (to stay static) in small chambers, (such as in the case of foams or porous building blocks, where the entrapped air does not escape and is stagnant), heat transfer is prevented additionally by convection.

Hence, light weight, aerated concrete building blocks or by incorporation of foamed plastic sheeting within the structure would be good strategies in heat insulation. Typical foamed plastics including rigid PU foam and EPS, and various other foamed plastics may be used [30]. Plasterboard can be obtained with a 25 mm foamed polystyrene backing and other composite sheet building products are available with PU foam cores. For these, fire retardant foams are available which meet the appropriate building and fire regulations.

Rigid foam structures of extruded polystyrene (usually coloured), EPS, (usually white coloured) and PU in the form of panels (as partial or complete building panels), boards and SWP are widely used in insulation, for exterior and interiors for energy conservation purposes. Spray-in place PU foam on the other hand, seals cavities almost completely, thus stopping convection and infiltration [31, 32]. PU foams have the highest R value of any insulation, although, they are not very cost effective. According to the APME, one kilogram of oil used in the production of EPS can save an equivalent of 75 kilograms of oil (in 25 years). The spongy, less brittle polyisocyanurate (PIR) foam with a very low thermal conductivity can even provide better heat insulation, or a given level of insulation can be obtained by using thinner sections of it. There is also Icynene foam to consider which is a modified lightweight urethane foam applied like PU, and water is used as a propellant, which stays soft and billowy when set, hence is expandable/contractible with the structure. Icynene is also available in spray foams and pour-in formulations.

EPS is a very effective insulating material and it has positive ratio of price to quality with excellent thermal insulation characteristics (0.040 W/m.K at a density of 15 kg/m^3 and 0.035 W/M.K at a density of 30 kg/m^3). EPS is used for roof insulation, insulation of walls and heat pipes, and for floors.

More information of polymeric foams are provided in Chapter 6.

Figure 3.2 presents heat insulation characteristics of different insulation materials with their average thicknesses to provide the same level of insulation.

In heating the building, one of the most important factors to consider is glass surfaces (its surface percentage, its arrangement, type of glazing involved and factors such as protection against the sun, etc.). Glass windows are the weak point in the chain, they offer little resistance to heat flow, and account for as much as 50% of the cost for heating and cooling in houses.

Conventionally heat insulation is applied (a) on the walls, (b) in the basement (under floors above unheated spaces, around walls in a heated basement or unventilated crawl spaces, as well as on the edges of slabs-on-grade) and, (c) in the attic (including the attic door or hatch cover). These are the main locations of heat loss in houses. It is estimated that, only air infiltration through openings in the house envelope can account for the 30-40% of heat loss in a typical home.

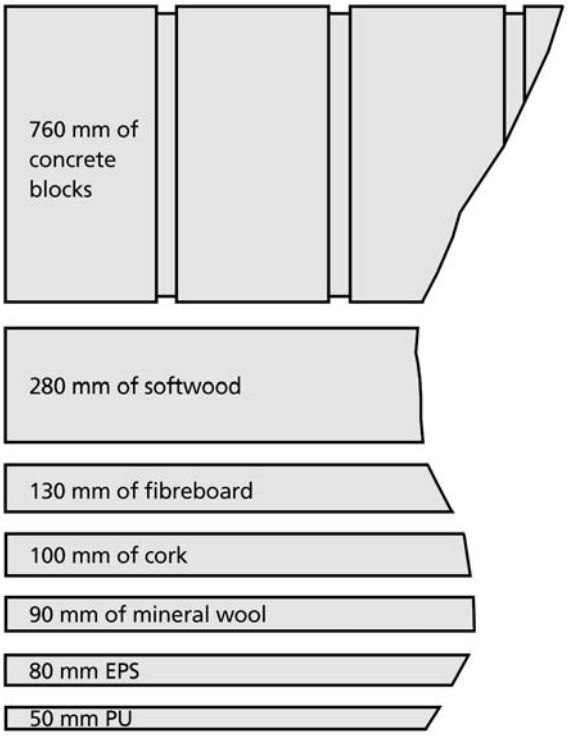


Figure 3.2 Different materials with their average thicknesses to provide the same level of heat insulation

In addition to the proper heat insulation, a vapour barrier on the inside walls and a vapour-permeable house wrap on the outside, should also be provided.

Infiltration is the loss or gain of heat through areas where inside and outside air, through leaks, meet. Many homes lose up to 30-40% of the energy used for heating and cooling through leaks, there are most common at outside doors that do not fit well or poorly set windows.

Heat insulation of exterior walls of buildings can be done by a variety of methods and rigid EPS foam is well suited for most of them, i.e., application of reinforced plaster renderings over EPS board, or use of EPS insulation board and a coating of fabric-reinforced plaster. A coating of EPS foam (2 m^2 of 10 cm thick) (which is equivalent to 10 litres of petroleum) can help to save 1200 litres of heating oil over a 50 year span.

In the case of cavity walls, either insulating boards are installed into the cavities (rigid insulation) or cavities are filled with PU foam (or prefoamed EPS particles), both foamed *in situ* by chemical reaction (foamed in-place) or by steam application (blown-in).

For insulation of floors: in addition to heat insulation, a certain degree of sound insulation must also be considered, which is usually done by means of a floating floor cover laying over an intermediate layer of elastified foamed boards, covered with a layer of PE film. Underfloor heating in houses, with an insulation layer below the underfloor heating, is usually combined with impact-noise insulations. Over hot (steam transfer) pipes, usually XLPE foams are used.

The insulation level of the existing home (retrofitting) can also be improved at any time.

The passive house is the ideal concept to reduce the losses of heat to such small amounts, that a separate heating system is no longer needed, (the EU Cepheus project on Cost Efficient Passive Houses [33]).

If the attic space is a part of the living quarters, sloping tile roofs need to be upgraded for further heat insulation, which can be done either above the rafters (between the roof framing and the tile covering. EPS with a density of 25 kg/m^3 is preferred for this application), or between the rafters (mostly EPS insulating boards are used, which permit some flexibility and transverse elasticity so that boards can be pressed in between the rafters), below the supporting roof structure, or by their combinations. In non-ventilated flat roofs, insulation with EPS foam (in the form of laminated boards or roll-on insulation) is done with units prelaminated with the roofing felt.

Adequate insulation and inhibition of air leakage in homes certainly means more effective conservation of energy and having a more energy efficient structure with big savings. However, it should also be remembered that insulating a house completely can bring several inconveniences as well, such as sick building syndrome (SBS) and increase of concentration of some harmful gases that may already be present indoors, such as formaldehyde, radon, etc., (for more information on SBS and harmful gases in houses, please also see Chapter 10).

In addition, thermal comfort is also an important factor in buildings; this is linked to the following four physical factors: the ambient room air temperature, the average temperature of room-enclosing surfaces, moisture content and movement of air within the room.

3.3.3.2 Moisture Insulation

Water can enter the house through a leaky roof or a poorly-sealed wall (mostly by capillary action for the latter), as well as through normal living activities in houses

(through cooking, bathing, washing, breathing, etc). Water entering the house can be avoided by improving the retrofitting and insulation. On the other hand, moisture generated moves from warm to cold areas in the house, through diffusion, and has a positive onwards pressure. Although water vapour can move through ceilings easily, it cannot do so through the (insulated) walls and it is trapped and condensed, affecting the R value of wall insulation and even causing rotting of some of the structural members. Increased levels of thermal insulation in buildings are also shown to lead to condensation and increased moisture [24].

Vapour retarders (VR; sometimes called vapour barriers, although this term is not correct) are usually used to retard (or prevent, in the case of barrier; which is not possible completely) moisture migrating the cavities of wall. Plastic films, membranes or coatings serve as VR, membranes are generally thin or thick flexible materials, in the case of the latter they are also called structural VR. Kraft paper or foil-faced insulation helps to slow the migration down in general, and for more severe cases, vapour-impermeable PE film on all exterior walls (under the drywall) is used. The type and kind of vapour retarder and its place of application depends on such factors as whether moisture is moving into or out of the house. If moisture moves both ways, even the application of a retarder can be avoided completely. Most paints and coatings also help to retard water vapour diffusion, this is known as the perm rating (any material with a perm rating of less than 1.0 is considered to be a VR). Glossy (acrylic) paints with a high percentage of solids and thick in application are especially effective (more so in colder climates). Polyvinylalcohol (PVA) is suggested as a coat (or its incorporation directly into the building materials) to control the moisture flow in and out of porous building materials [34]. Silicones have been used successfully in structural protection applications for decades, especially in water repellent treatments for building materials, such as roof tiles, and for protecting concrete and in masonry paints [35]. Thermoplastic lattices added to concrete and mortar can improve impermeabilities. Glass fibre reinforced polyester (the Glaswall system) can also be applied to vertical surfaces of concrete and brick to improve water resistancy of surfaces. However, in any case, in long lasting wall assemblies, one important characteristic of the wall is its ability to dry itself out if it picks up moisture for any reason.

The insulation system for pitched roofs usually provides the advantage of a continuous, homogeneous insulating layer with an economy in construction. Bitumen (asphalt) as well as its different versions modified with various polymers and a number of different roofing membranes, i.e., preformed or liquid applied sheets of PVC, terpolymer of ethylene-propylene-diene monomer (EPDM), chlorosulfonated polyethylene (Hypalon), PU, butyl rubber, polychloroprene (Neoprene) [36], all have been used as insulating layers.

More detailed information is provided in Section 3.3.5 and Chapter 5.

3.3.3.3 Sound Insulation

Sound and noise within buildings can either be of a general type (that is transmitted through walls and floors), or can be a specific noise arising from vibrating machinery (which can be eliminated by using proper vibration mounts). With general airbourne noise, the traditional method was to build very thick and heavy walls and floors with double windows, but, as buildings and walls have become lighter, other methods of sound reduction have become necessary. For ground-bourne or the structure-bourne noise, where vibration is transmitted up from the foundations, a different isolation approach is used. In principle, sound insulation can be provided by either 'a simple and heavy' or 'a light and complex' construction, of which the latter involves the use of rubber and plastics materials.

In many buildings there is a need to prevent external ground-bourne vibrations entering the building, (i.e., for those buildings that are close to rail and road traffic), which necessitates the incorporation of anti-vibration mounts during the construction of the building (in UK, laminated elastomeric bearings, and in France and Germany, steel coil springs, are often used). In this context, rubber blocks provide several advantages: (a) they are less massive than the equivalent steel springs for any particular application, and, (b) their dynamic properties can provide protection over a wider range of frequencies, particularly at high frequencies. One such big complexe supported solely on rubber blocks with a total mass of 24 K tons against ground-bourne noise is in Westminster, London, UK [10]. The Wellington Hospital in London which was built directly over underground tunnels and railway tracks was successfully supported on resilient rubber bearings giving rise to an isolation natural frequency of about 8 Hz in the building. Rubber vibration isolation bearing systems, although known for many years, have only during the last decades become available after high efficiency compound systems were developed, and it is estimated that their application can increase the cost of construction by up to 10%. With their high damping capacities and resiliencies, rubber bearings are unsurpassed materials, also used for the earthquake protection of buildings [10-14]. In Los Angeles, USA, the Law and Justice Center building is built to remain functional after an earthquake of 8.3 on the Richter scale, has 98 rubber bearings, each between 0.5-0.75 m in diameter with steel laminations and each weighing 500 kg. In such applications, the building sits on the bearings that isolate it from the ground and during a quake, the bearings intercept, absorb and damp vibrations, by lowering (or detuning) the buildings frequency below the earthquake's so that the structure moves like a rigid body instead of flexing, as a unit. The ultimate in earthquake-proof buildings is further improved in Japan by introduction of 'smart structures that can tune to the rhythm of an earthquake' by adding active computer controls [13], and elsewhere, by using electro-rheological fluids [37] and friction pendulum systems [13].

For adequate airbourne sound insulation in houses and offices, dry lining and composite wall panels incorporating foamed plastics are often used with walls. There is also the floating floor construction commonly used, where an air gap is created by placing a resilient material (rubber or foamed plastic) between the timber raft and the concrete floor.

Plastic composites are found to be effective in retrofitting masonry buildings to reduce seismic damage to remove seismic deficiency: the thin layer of reinforcement (fibre reinforced composite sheet) applied to the wall (like wall paper) is shown to increase substantially the load carrying capacities of masonry walls [38] as well as of reinforced concrete structures, including columns and walls and beam-column joints [39].

3.3.4 Sealant, Gasket and Adhesive Applications of Polymers in Housing Construction

3.3.4.1 Sealants and Gaskets

Sealants are elastomeric substances used to seal (or caulk) an opening or expansion/contraction joints in building structures against wind and water [40].

Seal joints can be expansion joints in concrete or masonry walls, they can be joints used between glazing materials and it's frames, or joints between precast concrete wall panels. Within these, polysulfides offer good resistance to chemicals and fuels, silicones provide performance within a wide range of temperatures [41], and urethanes provide abrasion and chemical resistant seals; all being elastic and flexible. A joint sealant is expected to be an impermeable material, mechanically proper, and durable that resists wear, indentation and chemicals as well as atmospheric conditions (with large changes in temperature cycling, moisture, UV irradiation and wind loads in expansion, compression and vibration [42, 43]. The life of a building depends largely on the ability of its external surface, including all joints and extensions, to withstand these conditions, and sealants are the most important to consider.

In glass-walled buildings, structural glazing high-performance two component sealants are used, which are usually of silicone and are designed specifically for use with metering and mixing equipment. In structural glazing, the sealant applied also acts as an adhesive to fix glass panels to the buildings framework.

Sealants are also known as 'adhesives with lower strengths', and they mainly comprise synthetic elastomeric thermoplastic or thermosetting polymers (pigmented/unpigmented).

(a) Thermoplastic sealants: vinylics (mostly PVC) and acrylics (mostly polymethyl methacrylate, PMMA) are used mainly in buildings for caulking and glazing, providing a maximum extension/compression range of ± 5%.

Thermoplastic sealants are, in general, either preformed sealants or hot-applied polymeric sealants.

Preformed sealants are pre-moulded from a range of materials (synthetic rubber, PVC) with different shapes (in tape, ribbons, beads, or extruded shapes), and are mainly used for glazing.

Hot-applied polymeric sealants are formulated with a carefully balanced blend of polymer with certain compounds, like asphalt, plasticisers and inert reinforcing fillers to produce a hot-pour point sealant with excellent bonding properties, high resiliency, ductility and resistance to degradation from weathering, to provide a positive seal during expansion and contraction of the joint.

Various grades of PVC sealants are commonly used in PVCu window and door frame applications and flexible PVC waterstops are mainly used to either keep water in as primary sealing system, (i.e., in pools), or out (in buildings below grade or in earth-retaining walls).

Acrylics, on the other hand, with good weatherabilities are used mostly for curtain wall panels as a sealant. Water-based (waterbourne) acrylic sealants and adhesives are well known. Use of thermoplastic elastomers is also increasing in various sealants applications.

(b) Thermosetting sealants are usually of the chemically curing type, high performance sealants, (i.e., polysulfides, PU, silicones, epoxy-based materials; all with maximum extension/compression ranges of ± 25, ± 25, 100 to -50 and less than 25%, respectively). These sealants are either (i) one- or (ii) two-component, or (iii) solvent release type, all with very good recovery capacities (>80%).

One-component sealants are mostly premixed sealants with polymer (can be of polysulfide, silicone or urethane-based) and the catalyst, which are paste-like materials kept at rather low temperatures (approximately –20 °C) that can be applied directly on site with a caulking gun after its thawing at room temperature, which cures chemically at ambient temperatures to give rise to sealants with rubberlike properties. One part silicone building sealants can be applied with an ordinary cartridge gun to porous (calcite-based substrates such as concrete, mortar, limestone, marble) or even non-porous (glass and aluminium) surfaces. These pre-prepared types have the advantage of their availability in a range of hardnesses from the softest types (used where there is maximum movement/minimum of strain) and medium grades (used if there is vibration movement) to hard types (for high abrasion resistance).

Two-part sealants, such as the chemically curing two-part polysulfide, silicone, epoxy or urethane resilient sealants, are applied on-site by mixing two parts: the polymer base part and the catalyst together and within the pot-life of hardening, which is usually one hour, the sealant is obtained. Chemically curing thermosets have much greater service lives than the others, and they usually need adhesion additives in order to achieve a proper bond to a surface.

Silicone-based thermosetting two-part sealants show high dependencies on environmental conditions for their cure rate (there is a longer curing period when temperature and humidities are low). Silicone rubber building sealants, for structural joints as well as for metal-to-glass joints remain flexible from –40 to 200 °C and resist prolonged exposure to harsh weather conditions and have better performances compared to polysulfide sealants, which are shown to loose their elasticities (after several years of sunlight, hot and cold weather cycling).

PU two-part sealants cure to a durable rubber consistency with high elasticity, abrasion/indentation resistance and bonding strength over a wide range of temperatures.

Epoxy resins also known as epoxides, are monomers (or prepolymer epoxies) that further react with curing agents (or hardeners) to yield the desired flexible, semi-rigid or rigid thermosetting plastics of liquid, paste or mortar consistency. The system is usually used in the semi-cured (non-crosslinked, uncured) state. Epoxies cure on their own under warm or cold conditions of application, where curing agents can be formulated to provide long or short pot lives, (i.e., slow cure, from 27 to 60 °C; normal cure, from 5 to 60 °C and rapid cure, from –18 to 60 °C). There are also special formulations for super rapid cure which has a potlife of 30 seconds. Polyurea seals are 100% solids, with high elongation self-levelling elastomers. They are volatile organic compound (VOC) free, used in horizontal saw or preformed joints on concrete or asphalt.

Within solvent release type thermosetting sealants, there are Neoprene, butadiene-styrene, chlorosulfonated polyethylene, EPDM, and silicones. Solvent release types constitute the largest variety of sealants and are composed of three parts: (1) the liquid portion of the compound which is the basic non-volatile polymer/elastomeric vehicle, (2) the pigment component, and a (3) solvent or thinner component used to ease the process and to control the thickness. The sealant is cured and its required viscosity is controlled by the evaporation of solvent.

Gaskets are in the form of thick ribbon (tape) sealants which are widely used with glazing and for precast concrete panels in certain walls. Elastomers are also used as piping gaskets, and in civil engineering for a range of applications, (i.e., as bridge and other structural bearings, and expansion joints etc).

3.3.4.2 Adhesives

Adhesives, are substances capable of holding two or more surfaces together in a strong, often permanent bond, which may provide a specific function in themselves as well (such as protection, decoration, etc.) [44, 45]. Adhesives can be classified by their reaction to heat (thermoplastic/thermosetting) and their ability to remain rigid or not (elastomeric

adhesives). Large scale modern application of adhesives is essential to the construction industry in such materials as plywood, laminated beams (wall partitions in floors and ceilings). Polyvinyl acetate (PVAc) can be used between two pieces of wood as an adhesive to glue the pieces together, and adhesive bonded connections are frequently used in construction. In this context, adhesive bonding of FRP composites introduces some problems. Currently epoxy and acrylic-based toughened adhesives are used frequently for general applications.

Epoxy resin, as an adhesive, is used for many applications in building/construction, (i.e., it is possible to bond a new rebar to existing steel in concrete instead of welding it, by use of special epoxy adhesives). Epoxy can bond to almost any material (for structural or non-structural bonding) with high adhesive strength in various environments and temperatures. In civil engineering applications, epoxy adhesives are used to bond concrete in a number of different ways. Epoxy can be used to bond plastic concrete (or wet concrete) to cured concrete, it can be used to bond cured concrete to cured concrete, or cured concrete to cracked concrete, as well as to bond cured concrete to other materials with similar or dissimilar thermal expansion coefficients and elastic moduli.

Although the expansion coefficient of epoxy is two-to ten times that of concrete, use of fillers in the epoxy helps to adjust it to the level of concrete [46]. For bonding surfaces (such as steel and concrete, but not composite surfaces), an adhesive-compatible primer coat is usually needed. However, recently an adhesive has been developed which does not need any activators or primers that can be used to bond composites, metals glass, ceramics, plastics and wood successfully [19, 47].

3.3.5 Roofing and Flooring System Applications of Polymers in Housing Construction

3.3.5.1 Roofing

The ultimate life of a building depends on a reliable roofing system. Water seepage due to rain or any other sources gradually damages the concrete and cemented roof at first and then percolates through the walls of the building. This process ultimately causes severe damage to the whole construction, if proper waterproofing measures have not been taken care of. The problem is highly acute in the areas where there is a high rate of rainfall. In all cases, the roof system is expected to withstand wear, tear and atmospheric conditions: while still remaining watertight.

In the traditional waterproofing systems, bitumen (or bituminous felt) was used commonly in the so-called 'built-up' roofs. Since the introduction of plastic films, sheets of mainly

PVC and PE have played a major role in the shift of early roof waterproofing technology and materials. After the introduction of elastomeric and other thermoplastic materials, flexible membranes of polychloroprene (Neoprene) rubber, butyl rubber and Hypalon were used. Later on, liquid PU, solvent-based liquid acrylate and liquid EPDM systems, in addition to new materials like SBS modified bitumens, were also used in the management of roofing. All fall into the 'single-ply' family of roofing, which offers a much cleaner, safer, energy-efficient and cost-effective alternative to built-up roofs.

In selecting efficient (waterproofing) systems for roofing out of all the materials tested, elastomeric membranes of EPDM rubber has been well known since the mid 1970s as providing the most effective moisture protection, which is highly cost-effective, has excellent weather resistance, is light in weight and easy to install even on the old and used building roofs, is rot proof and has a very long maintenance-free service life as well. In addition to its use in roofing, EPDM membranes can also be effectively used as various damp-proof linings to provide excellent moisture barriers in the water management sector (like canal linings, acid and alkali resistant lining in effluent treatment plants, in covering car parking decks), and can also be used as geomembranes. In the commercial construction market, use of EPDM single-ply materials has continued to grow in the roofing and waterproofing sectors at a steep rate in many countries now.

Details of EPDM membrane and its applications in roofing is presented in Section 3.5.

Wired glass and corrugated plastic sheeting (mainly glass fibre reinforced unsaturated polyester for the latter) have been used in the past for roofing in conservatories and buildings, where transparent panels are required and, in recent years double and triple walled polycarbonate (PC) and PVC sheeting (in clear and bronze colours) have become available and used to provide diffuse daylight for illumination and heat insulation. PC sheeting are light in weight, have high resistance to breakage (250 times stronger than glass), can be cut-drilled and machined, can be cold formed (or thermoformed) into a number of shapes to provide attractive and functional curved surfaces, and rigid enough to handle. UV stabilised grades of PC are used, in some cases with an additional UV barrier film incorporated under the outer skins and for its fixing, aluminium or PVCu glazing bars are used.

3.3.5.2 Floors and Flooring

A number of different materials have been used as flooring material, beginning with rubber (1894), cork (1904), asphalt (1920) and linoleum until after World War II, when easy-to-maintain and more durable vinyl (resilient) flooring was introduced. Today, use of vinyl flooring is second to wall-to-wall carpet application in floor covering sales in

USA. Originally used only in high traffic areas, vinyl flooring (both sheet and tile) is the most popular choice for any hard-surface application, and flexible PVC-P [plasticised by a series of phthalate plasticisers, like di-isononyl phthalate (DINP), di(2-ethylhexyl) phthalate (DEHP), benzylbutyl phthalate (BBP) and di-isoheptyl phthalate (DIHP)] floors are commonly used in nursing homes and hospitals, in particular in operating theatres where proper cleanliness is vital, in addition to their use in houses. Vinyl flooring reduces noise and provides comfort underfoot, and are resistant to impact (static as well as rolling) loads. Vinyl (resilient) floors accounts for about 10-12% of all floor covering materials and typically contain fillers, plasticisers, stabilisers and pigments, in addition to the basic ingredient of PVC resin (which may change between 10-55%). Producers of PVC floor coverings have begun to substitute the controversial DEHP phthalate plasticiser with much safer ones [48].

There are some applications of rubber flooring, and EPDM rubber is recommended by the Danish Environmental Protection Agency as an alternative to PVC use.

3.3.6 Glazing, Plastic Lumber, Paint, Wall-Covering, and Other Applications of Polymers in Housing Construction

3.3.6.1 Glazing

Glazing is one of the external surfaces of the building which causes most of the thermal losses, either by conduction through the glass, around the window frame or by infiltration. Glazes allow penetration of light into houses, provide visual comfort, privacy, and may help to reduce heating and cooling costs. Still, it is estimated that about 20% of the energy used for space heating in houses is being lost through glazing, because windows are not very effective heat flow inhibitors (both in winter and summer) of the building's shell.

The thermal performance of glazing is characterised by the U factor (the heat transfer coefficient or heat loss factor); the lower the U value of a glazing the lower the heat loss, and it is important that the U value is given for each type of glazing

Until recently, clear glass was the primary glazing material used. Glass is durable and allows the passage of a high percentage of sunlight, but it also has little resistance to heat flow. However, during the last two decades, glazing technology has changed considerably. The advanced glazing systems include double- and triple-pane windows as well as use of glass with special coatings (of low emissivity, known as *low-e*, spectral selective, heat absorbing –*tinted* or reflective) and with other applications (gas filled windows), or combinations of these. Within these, it is estimated that, if all single and double glazing in EU dwellings is replaced with low-e double glazing, there could be more than 1 million gJ

(or 26 million tonnes of oil equivalent (ToE)) savings, amounting to 14,264 million Euros each year [49]. 'Super-windows' with multiple low-e glazing and low conductance gas filled barriers between panes to reduce convective circulation of gas filling, insulating frames and edge spacers, give the highest thermal resistances. Chromogenic (smart windows with optical switching) adaptable glazings, either of *passive* (capable of varying light transmission characteristics according to changes in sunlight – photochromic; or capable of changing heat transmittance characteristics according to ambient temperature swings – thermochromic) or *active* (where a small electrical current is used to alter the transmission properties – electrochromic), are potential new applications.

Table 3.1 presents U-values of three major types of glass products that are being used in dwellings.

Table 3.1 U-values of three major types of glass products used in dwellings [49]

Type of glazing	**Typical U value of glazing unit ($W/m^2.K$)**
Single Glazing (from one single pane of 4 mm glass)	4.7
Double Glazing (from two glass panes of 4 mm in a factory-sealed unit, with an air gap; 4/12/4 mm. arrangement)	2.7
Double Glazing, with low-E glass coat (from two glass panes, of 4 m one with special coating in a factory-sealed unit, with an air gap (12 mm); 4/12/4 mm arrangement)	1.6

The following polymeric materials are being used as a substitute for glass for window panes, glazing sheets and transparent sheet applications [50]:

(a) Acrylic-based polymers, such as PMMA,

(b) PC,

(c) Polystyrene (PS), and

(d) Transparent glass reinforced polyester sheets

The demonstration house designed and constructed by NESTE (Helsinki, Finland) incorporates many building components and materials all made of plastic (75%), featuring see-through silica modules as window glass and crystal-silicon sun shades on the south facade to reduce summer cooling loads, while GE Plastic's 'living environments model

house' has a characteristic foyer, rich with PC glazing. PC, in addition to its strength and high transparency, also provides toughness enough to withstand abuse, and is ideal for roof-glazing. Glass-walled buildings are becoming a feature of most European cities in the last decade, where structural glazing high-performance sealants are used.

Passive solar heating and cooling is the most cost effective heating/cooling system in houses. Solar energy falling on the roof is generally much more than the total energy consumed in the house. Solar energy is in the form of heat and light, and about 35-40% of it reaches the earth. When sunlight in the form of short wave radiation strikes a surface, it is 'reflected, transmitted or absorbed (transformed to heat)', depending on the nature, colour and clarity of the surface; and heat absorbed is redistributed evenly through the solid mass (conduction of heat). Heat transfer from a solid material to liquid or air occurs by radiation (infrared) and it may be either via natural or forced convection. Gases and plastics are known as poor (and metals as better) heat conductors. In this context, a good storage material is expected to absorb heat easily/and give it back when needed; and it must be a good heat conductor. Radiant energy is limited to infrared radiation emitted from a material at ambient conditions, which depends both on the temperature of the material and the characteristics of its surface, i.e., polished metal surfaces are poor emitters/poor absorbers of thermal energy, and, glass is less transparent to most thermal radiation (it transmits nearly all solar radiation by letting radiation to move through). Hence, solar energy passing through the windows can be absorbed by interior materials mostly, and re-radiated into the interior space in the form of thermal energy (heat).

In passive solar designs: the windows, walls, floors, and the roof are all used as the heat collecting, storing, releasing, and distributing system. Firstly there is a transparent material (glass or plastic) with a south facing exposure to allow effective entry of solar energy and secondly a material inside (normal walls/water wall, floor and ceiling) to absorb and store the heat (or cool) for later use; where the collection and storage of heat with convection process is foreseen. In this design, the system (the mechanism of heating and cooling equipment) is integrated into the building elements and materials. Passive solar systems can also be isolated gain type, which uses a fluid (liquid or air) to collect heat in a flat plate solar-collector attached to the structure, and again by natural convection, heat is transferred through ducts or pipes to a storage area where the collected cooler air or water is displaced and forced back to the collector.

3.3.6.2 Plastic Lumber

Recycled plastic lumber (RPL) was developed as a substitute for treated wood [51]. RPL, being a product of commingled plastics, can contain as much as 100% post-consumer plastics (or a blend of recycled plastic and recycled wood waste), while 'structural plastic lumber' is

a high-performance construction material consisting of a patented formula of recycled plastic, fibreglass, and selected additives; with improved stiffness and strength. If compared with wood, unreinforced RPL, (RPL-U) has lower stiffness values (modulus of elasticity of RPL-U is lower by an order of magnitude). RPL is also significantly viscoelastic (it's mechanical properties are time- and temperature-dependent and are subject to permanent deformation (creep or sagging) under sustained loads (the rate of which depends on the magnitude and duration of the stress, and temperature). Dimensional changes due to temperature are also bigger in RPL than in wood. RPL are machinable like wood and, in fact, hold nails and screws better than wood. RPL are virtually maintenance free and last for 50 years.

RPL products offer inherent resistance to insects, rot, moisture, chemicals and to the environment, and are an excellent alternative to chemically treated wood, because they do not leach toxic chemicals into the soil. They are available in different colours both for commercial and residential applications. RPL are applied mainly outdoors (as decks, docks, bulkheads, landscaping, fencing, window and door trim, benches, tables, playground equipment, pallets, and even in foot bridges, etc.), with the possibility of uses indoors (for shower stalls, counter tops, base boards). Plastic lumber is extremely well-suited and applied to the walking surfaces of decks and marine docks, as well as for railings and industrial cribbing/blocking. It is usually not well developed in load-bearing applications such as joists, beams or studs. However, the added fibre (typically fibreglass or wood) gives additional stiffness and strength to the lumber, improving its performance in structural applications. If RPL-U is used as decking boards, especially if the span is too big, joist spacings are decreased and/or thicker deck boards are used to avoid creep (under its own weight).

The American Society for Testing Materials (ASTM) established structural and property standards for plastic lumber, ASTM D6662, in 2001 [52].

RPL and structural plastic lumber still is not well accepted and used by the construction industry, most probably due to processing deficiencies, product inconsistencies, and price volatilites; although a number of projects already undertaken have proved its value and importance in the sector, for example:

(a) *Decking boards in a boardwalk at Kelleys Island on Lake Erie, Ohio, USA,* where 180 m boardwalk in a wetlands area was selected as a demonstration project,

(b) *Bridge at Fort Leonard Wood, MO, USA*, was developed to demonstrate the structural capabilities of plastic lumber. The 7.6 m by 8.1 m plastic lumber bridge sitting on six steel girders which is used primarily for pedestrian traffic and to carry vehicular loads. The bridge is expected to last 50 years with no maintenance. For the plastic lumber preparation, 5900 kg of waste plastics (equivalent to approximately 78,000 (3.79 litre) HDPE milk jugs and 335,000 (240 ml) PS foam coffee cups) were used.

(c) *Floating docks for the Op Sail 2000 event in New York, NY, USA*. Since chromium copper-arsenate-treated wood poses an environmental hazard, RPL use in marine and waterfront applications, is most suitable. This demonstration project showed the viability of RPL for floating docks (seven of them were built) during the Op Sail event with tall ships in New York Harbor, and to date, they have all been working successfully.

(d) *Elevated platforms at the bob-sled and luge track, Lake Placid, NY, USA*. This was the first major project where reinforced structural plastic lumber was used (in joists, beams, girders, and decking boards). RPL platforms were designed and installed at low temperatures of –40 °C in time for the start of the games, and one particular platform was tested for creep under sustained loading with sandbags with 490 kg/m^2 loading for a year.

(e) *An arched truss bridge near Albany, NY, USA*, which is a 9.1 m span bridge used as a demonstration project to investigate the performance of structural reinforced RPLs in the form of laminated beams.

(f) *Plastic lumber railroad cross-ties* (supporting 240 ton locomotives that need to be replaced about every 12 years, in place of chemically treated wood ties), and,

(g) *A bridge made primarily from plastic lumber* supporting up to 30 tons (Ft Leonard Wood in St. Robert, MI, USA), designed to last for 50 years.

3.3.6.3 Paints

Paints are used for cosmetic as well as protective reasons (in the form of coatings). Within this group, there are acrylic paints commonly used which contain PMMA in a solvent (which evaporates as the paint dries), which makes the paint surface, hard, tough and shiny. Since PMMA is hydrophobic, to make the acrylic paint waterbourne, poly(vinyl alcohol-co-vinyl acetate) copolymer is generally used, where PMMA can stay suspended in water, (known as PMMA latex and latex paints).

More detailed information on the subject is provided in Section 3.4.

3.3.6.4 Wall-Coverings

Wall-coverings (or wallpapers) are one of the flexible PVC applications in residential and commercial interiors. PVC wall-coverings contain a number of additives (plasticisers, stabilisers and other additives, such as pigments, mildewicides, fungicides, flame retardants (or smoke suppressors), as well as low levels of biocides) in addition to PVC. They are used both as decorative as well as for protective purposes, they are fairly impermeable

for water and can act as a vapour barrier trap (known as concealed condensation), they can provide energy savings and enhance the durability of the wall. In the case of concealed condensation, growth of mildew over time can occur, and use of a permeable membrane on the outside wall can help to vent moisture. Certain 'microvented' breathable wall papers are also available.

Most wall-coverings have three layers: (a) the decorative (top) layer, (b) the intermediate (ground) layer, (c) the substrate (or the backing) layer.

Vinyl wall-coverings can be categorised in general as: vinyl coated paper, paper backed vinyl or solid sheet vinyl and/or fabric backed vinyl and rigid vinyl sheet without a backing.

Wallpapers often have coatings made of PVA and other ingredients to make them shiny.

3.3.6.5 Blinds, Fencing, Decking and Railing

Blinds are typical examples of non-structural applications of plastics, used to filter the UV and infrared rays when applied to windows, allowing for diffuse lighting. They are preferably produced from PVC-P or rigid, translucent or opaque, with a range of flap sizes and colours.

Fencing, decking and railing, are mainly made of reinforced PVC, and are another series of non structural application of plastics products for outdoors. The use of vinyl fencing, decking and railing is becoming one of the most cost-competitive outdoor living products used in place of traditional wood and/or metal, including high-rise apartment balconies and stadium guardrails and front porches. In fact, plastic fencing is reported as the fastest growing segment (with an approximately 30% annual growth rate) and at current growth rates, they could account for 30% of the residential market by 2007 [53].

GFR polypropylene-based composite fence (with 75% glass fibre and the rest being chemically coupled, heat and light-stabilised PP concentrate), which is fade-resistant and with the matte finish look of wrought iron, is shown to be 60% stronger and more flexible than aluminium; it absorbs impacts and becomes more rigid than aluminium allowing the fence to withstand better, heavier impacts at higher stress loads.

3.4 Coatings

Dorel Feldman

A coating is a material that is applied to a substrate surface and which becomes a continuous film after drying. The terms coating or surface coating and paint are often

used interchangeably. The purpose of their application is aesthetic or protective or both. It has become common practice to use coatings as the broader term and to restrict paints to the architectural and household coatings.

Emphasising the importance of aesthetic factors is not to overlook the important protective role that coatings play against moisture, UV light, chemicals (including pollutants), abrasion and freeze-thawing. The use of metals in construction would be restricted without protective coatings. On an inert surface, coatings will last longer than they do on many common building materials. Movement in wood can lead to the flaking of paint; conversely, an impermeable coating contributes to wood decay if moisture is trapped.

For the interior of buildings, the paint has a special effect on illumination; white and pastel colours increase the availability of natural and artificial light and influence mood and feelings.

From the point of view of applications, coatings are grouped into architectural, product coatings and special purpose coatings.

Architectural coatings include the familiar paints and varnishes (transparent paints) used to decorate and protect exterior and interior of building, undercoaters, stains, primers and sealers.

Product coatings called also industrial coatings or industrial finishes are applied on automobiles, machinery, equipment, appliances, wood products, etc. [54, 55].

A coating formulation is based on a film former (the binder), the pigment, a volatile component, and additives. The main component, the binder is an organic film forming polymer. Most of the coatings contain a finely divided insoluble pigment that provides colour and opacity. For steel, anti-corrosive pigments are used. The coating fluidity necessary for application is obtained with a volatile liquid (solvent, diluent, extender). While solution viscosity increases with the molecular weight (MW) of the polymer, the viscosity of emulsions or dispersions is independent of the MW. The choice of the solvent depends on the type of polymer used. Stabilisers for long shelf life and flow modifiers (thixotropic agents) are sometimes necessary. Coating products must resist irreversible changes such as skinning or coagulation.

To reduce the amount of VOC emissions, an important continuing drive in the coating domain is to decrease the amount of organic solvent by replacement with water. Waterbourne coatings are products with aqueous media. Sometimes the term water-reducible coatings is used for waterbourne products, including latices based on hydrophilic resins. Radiation curable and powder coatings don't contain volatile solvents.

Whilst the move to waterbourne systems offers advantages in terms of environmental pollution, additional disadvantages may be introduced in climates where the evaporation of water is too slow as in cold or high humidity areas.

Complete removal of residual organics from waste water is extremely difficult and costly but techniques for using supercritical fluids like carbon dioxide for stripping such compounds from waste water are already being used [56].

The main requirements for coatings are: durability, opacity, gloss, adhesion to substrate, colour, protection, and specific physical properties. Durability is considered as the degree to which surface coating systems withstand the destructive effects of the environment which can involve weathering as well as mechanical wear and attack by corrosive substances [57, 58].

A typical architectural paint for metals or wood may contain:

(i) *a primer* to improve adhesion to substrate and undercoat

(ii) *an undercoat* which has to contribute to the obliteration of the substrate and provides a smooth surface upon which to apply the topcoat

(iii) *a topcoat* which is not pigmented provides the aesthetic effect [59].

The progresses made in the formulation of coatings, both low temperature application and low VOC emissions, have proved to be very advantageous for painting. A smarter approach to the mixology of these paints holds great promise for the future. They dry faster than common paints, they resist frosting, peeling and blistering because of the cold weather [60].

3.4.1 Polymers Used for Coatings

Some natural products and a lot of synthetic polymers are used in coating production – they can be grouped as:

(a) oils, natural polymers (resins, cellulose, starch, proteins), and modified natural polymers, (i.e., nitrocellulose)

(b) polymers obtained through polycondensation or polyaddition (polyesters, alkyds, PU, epoxy polymer (EP), urea formaldehyde(UF), phenol formaldehyde (PF))

(c) polymerisation polymers (vinyl, copolymers, etc.)

More recently, coatings based on synthetic polymers are divided into solvent-based or water-based.

3.4.1.1 Natural Products and Modified Natural Polymers

Vegetable oils and their derived fatty acids play nearly as important a role in surface coatings today as they did in the past because of their availability as a renewable resource, their variety and their versatility [61].

Triglyceride oils such as linseed, tall, tung, castor, vernoia and other highly unsaturated oils are used as the basis for oil-based formulations. They cure by an oxidative mechanism, forming ether bonds between the trygliceride molecules, and through oxidatively initiated free radical reactions attacking the double bonds, leading to a three-dimensional polymer.

The following stages can be distinguished during the formation of the film based on drying oil:

(a) auto-oxidation, where oil reacts with oxygen to form peroxy compounds

(b) peroxy compounds decompose to create covalent bonds between the triglyceride molecules

(c) the film continues to react by ageing, forming additional crosslinks, some volatile products and eventually chalking [62, 63].

Castor oil and vernoia oil are also based on tryglycerides, but they bear different functional groups. The first contains hydroxyl and vernoia oil epoxy groups. When one of these two oils reacts with difunctional sebacic acid, a three-dimensional esterification reaction occurs, forming a network [64, 65].

Metals (Co, Pb, Ca) added as soaps of long chain acids (naphthenates) usually catalyse the auto-oxidative crosslinking of tall oil with a high content in polyunsaturated fatty acids.

Shellac is a natural resin produced by refining an insect (*Coccus laca*) secretion. It is soluble in alcohol and other organic solvents but resistant to hydrocarbons and widely used as a wood coating. It has good abrasion resistance and adheres well to metals.

Unlike nitrocellulose, which is still used for lacquers, other cellulose esters (cellulose acetate, cellulose acetate butyrate) have been used in the past as coatings for different materials.

Vegetable and animal proteins, which are often abundantly available as by-products of the food processing industry, are among the biopolymers being used or investigated as feedstocks for the production of films and coatings. In recent years, the scientific literature worldwide has seen an explosion of published papers, often the product of interdisciplinary research, related to protein-based films [66].

3.4.2 Solvent-Based Coatings

Organic solvents are used in coating formulations for their preparation and application. When the organic liquid is not able to dissolve the polymer binder it is preferable to call it the diluent. In case of the water-based coatings, water can act as a solvent for some components, but as a non-solvent for the synthetic polymers.

Solvents can have harmful effects on humans arising from their carcinogenic, mutagenic and reprotoxic properties. In their selection the following criteria have to be considered: evaporation rate, polymer solubility, activity, flash point, density. Evaporation rate can affect the drying time and film formation. As evaporation proceeds, the coating composition varies, during this change it is important to maintain solvency and to avoid polymer precipitation. A high flash point is always preferred and a lower density besides other advantages confers economic benefits since less weight is needed to fill a given volume [67]. Flammability also poses a significant hazard regarding the storage, handling and use of organic solvent-based coatings.

For many applications, the most effective blends have been based on ketones and aromatic hydrocarbon solvents currently restricted as hazardous air pollutant (HAP) products. Since new solvent systems will have smaller amounts of HAP, the blend cost is likely to rise. Methyl *n*-amyl ketone (MNAK) and *n*-butyl propionate (BuProp) are attractive from the point of view of the environment and their physical properties [68].

In the first stage of organic solvent evaporation, its rate is independent on the presence of the polymer. Evaporation rate depends on:

(a) the vapour pressure at a given temperature

(b) the ratio of surface area to the volume of the film

(c) the rate of air flow over the surface.

During evaporation, the viscosity of the system and glass transition temperature (T_g) increase, free volume decreases and the rate of loss of solvent from the film becomes dependent not on how fast the solvent evaporation will take place but rather on how rapidly the solvent molecules will diffuse through the film [54].

More often the solvent-based coatings are made of alkyds, acrylics, PU or EP polymers. Alkyd-based polyols and unsaturated dibasic acids were the first synthetic polymers used in coating technology. It was successful in chemically combining oil or oil derived fatty acids into a polymer structure, thus enhancing the mechanical properties, drying speed and durability over and above those of the oils themselves and the oleoresins then available [61].

Aromatic acids such as phthalic anhydride of isophthalic acid and maleic anhydride contribute to the hardness, chemical resistance and durability. Long chain dibasic acids such as azelaic are sometimes used to provide flexibility. The used polyols are at least trifunctional to permit branching or crosslinking. The oil content may vary from less than 40%, up to above 60%. Alkyds with more than 60% drying oils are soluble in aliphatic solvents and are drying slowly to give soft films with poorer gloss retention and durability. Alkyds with less than 60% oil give less flexible films with good gloss retention and chemical resistance. Alkyd modification can be done with PU, polyamide (PA), silicone, PF, amino resins or with vinyl monomers such as styrene, vinyl toluene, methyl methacrylate (MMA) and butyl-methacrylate [69].

Acrylic coatings can be applied as solutions, aqueous emulsions, and powder. The methacrylates are more resistant to alkalis than the acrylates [70].

The most important types of PU coatings are based on two component systems, an isocyanate prepolymer and a polyol. Coatings based on high MW thermoplastic PU dissolved in a solvent are used, and they are cured by the evaporation of the solvent [71]. Other PU coatings applied for flooring are formulated for radiation cure or vapour cure. At the initial stages of the crosslinking reactions, solvent evaporation competes with the PU network formation and isocyanate consumption changes at various depths from the film/air and film/substrate interfaces [72].

For EP coatings, the most common commercially available is the 'two package' type coating used for floor toppings, tank linings and as heavy-duty industrial marine maintenance product [73]. The crosslinking agents reacting with epoxide and hydroxyl groups result in highly chemical and solvent resistant films because all the bonds are relatively stable [74].

One of the new technologies that have arisen in response to economic pressures, to reduce energy or the use of petroleum derived solvents and concern with environmental pollution and occupational health is that of producing high solids coatings [75]. In such products, low MW resins are used to keep a low solution viscosity, and after curing they convert to three-dimensional networks.

Solvents can be replaced with reactive diluents like some monomers, as is the practice with unsaturated polyesters and with radiation-curing polymers. Polyfunctional monomers like unsaturated melamine resins are becoming used as diluents for alkyd resins [61].

3.4.3 Water-Based Coatings

The environmental drive for the replacement of solvent bourne coatings with their aqueous-based counterparts has forced the world coatings industry to develop new

polymer technologies to overcome the technical hurdles involved in the production of the VOC coating systems. The trend is to move away from solvent bourne coatings with higher VOC content to high solids/low solvent, waterbourne, or radiation curable liquid and powder coatings [76].

For water emulsions, one of the main parameters is the minimum film forming temperature, implying the temperature at which the polymer still forms satisfactory homogeneous films. Beside others, the T_g of the polymer determines this parameter.

There is a growing interest in water-based coatings for a number of reasons, the most important being the increasing environmental legislation, health aspects and the lack of flammability.

3.4.3.1 Alkyd Coatings

Alkyds are among the first water-based coatings. An alkyd emulsion is a dispersion of an alkyd resin in water. Unfortunately, almost all dispersions are unstable from the thermodynamic point of view - droplets will coalesce together in an irreversible way once they come too close to each other. In order to assure that all the particles repel each other strongly enough to withstand all the external influences, the mechanism called electrostatic repulsion or the steric (osmotic) repulsion is used. A fundamental study [77] on alkyd emulsion paints has arrived at the following conclusions:

(i) The type of colloidal stabilisation of pigments and resins should be identical to assure optimum stability, gloss and other properties.

(ii) The rheology of dispersion paints can be improved by using hydrophilic thickeners.

(iii) The use of anti-skinning agents should be avoided, provided that the stability of the alkyd emulsion is satisfactory.

(iv) Excellent properties can be obtained by using alkyd emulsions.

After the application of alkyd coating, the physical film is formed together with crosslinking (known in coating industry as curing) by means of oxidative drying, identical to the crosslinking of solvent-based alkyds [78].

The replacement of organic solvent by water poses a number of challenges to both resin and additives, particularly in the areas of film mechanical properties and durability. The low photochemical resistance of many polymers limits their use in coatings, mainly those designed for exterior applications such as exposure for long time to sunlight. Where

necessary, modifications with PU and acrylics will improve drying characteristics and stability. The latest developments are so called 'core-shell emulsions' which are produced from alkyds with low acid values and a surplus of hydroxyl groups [79].

Significant improvements have been observed in the properties of alkyd resin after modification (grafting) with acrylates. The incorporation of MMA into alkyd at a level of 30-40% yields a binder suitable for formulation of high performance exterior paints [80].

3.4.3.2 Acrylic Coatings

One of the most important groups of film forming latexes used in waterbourne coatings is the group of acrylic resins. These are for the most part, the polymers obtained from acrylate and methyl acrylate esters of lower alcohols, of which methanol and butanol have the widest application. Those based on MMA and butyl acrylate (BA) yield copolymers with good film properties [81].

The development of associative thickeners during the 1980s saw a significant advance in the rheological performance of acrylic emulsion paints and has assisted their ingress into high performance sectors of the coating market. The new thickeners (polyether-based PU, hydrophobically modified carboxylated polyacrylates and hydrophobically modified cellulose derivatives) offer substantial benefits. Coatings produced with such polymers show rheology more akin to that obtained with solvent bourne alkyd systems, and as a consequence offer improved flow and levelling and film build, improved brushing properties relative to cellulosic-based thickening agents, improved pigment dispersion, and thus excellent gloss in conjunction with the best acrylic latex technology.

Although paint films based on the hydroxy acrylic, grafted acrylic and low T_g acrylic polymers have in general good properties, the films containing the grafted copolymer exhibit superior flexibility and impact strength. The accelerated weathering of the pigmented films based on the grafted copolymer is intermediate to that of parent polyacrylic and low T_g polyacrylic films [82, 83].

The prospects for acrylic latex paints in the masonry market are much brighter today than in the past due to the many advances in acrylic emulsion chemistry. Besides the unsurpassed exterior durability (tint retention, chalk resistance and water resistance) and good adhesion that acrylic chemistry brings to all exterior coating applications, the acrylic technology, provides features uniquely suited to the masonry market, including resistance to alkalinity, good holdout, resistance to efflorescence and cracking. Especially important is the very good alkali resistance provided by acrylic binders. This attribute enables paints formulated with these latexes to be applied over highly alkaline, damp,

fresh masonry without difficulties. In contrast, paints formulated with solvent bourne oleoresins binders tend to degrade rapidly when applied to these materials.

A recent study [84] regarding the application to wood of this group of coatings, shows that the adhesion values of alkyd emulsion paints were much lower than the values of the acrylic dispersion paints under dry conditions. The adhesion was much higher for small particle dispersion paint, due to the improved penetration of the small acrylic particles into wood and/or to an increased contact area between this paint and the wood substrate due to a more packaging of the particles. Under high moisture conditions the adhesion values of the acrylic dispersion paints decreased to a high extent.

Silicon-acrylic resin systems using the crosslinking technology overcome at least some of the defects of conventional waterbourne coatings [85].

Polyaminated dispersants are able to stabilise the fine dispersions with inorganic or organic pigment [86].

In the early 1990s, the drive for higher performance coatings with lower VOC content led to the commercial introduction of waterbourne acrylic-epoxy coatings. These are two component coatings, with one component containing carboxyl functional acrylic latex, and the other component containing an EP emulsion. Upon mixing, cure is believed to proceed via carboxyl-epoxy reaction and/or EP homopolymerisation. It is interesting that although these reactions usually proceed slowly under ambient conditions, the applied coating has attractive properties [54].

3.4.3.3 PU Coatings

These products can be broadly defined as coatings that contain the *urethane* or *urea* groups. To a lesser extent, groups such as *allophanate* or *biuret* can be present. They are available one or two component systems, able to cure at room or higher temperature. These coatings can be based on linear PU dispersions, or crosslinkable dispersions and they can also be produced by solvent free processes.

Linear PU dispersions can be obtained by the so called 'acetone process'. An isocyanate-terminated PU is made in acetone solution from diisocyanate and a diol (or mixture of diols). The chain extension is obtained with a substituted diamine. After dilution with water, acetone is removed by distillation. The crosslinkable PU dispersions can be produced by one-step or by two-step process [71].

A preferred route to stabilise PU dispersions involves the existence of ionic groups in the PU macromolecules in the presence or absence of additional nonionic emulsifier.

The weatherability of PU coatings depends on the nature of both main components: the isocyanate and the polyol. From the weatherability point of view, the following order was established: polyethers<polyesters<acrylic polyols.

While the latter two provide more UV stability, those based on polyether polyols have a better hydrolysis stability [87].

Two component PU have been used successfully for several years and are proven energy-efficient systems. Recent developments have yielded higher solids components and these should be considered for applications where high performance VOC compliant coatings are needed. PU coatings are ideal candidates to satisfy the demands of specific segments of the architectural and maintenance coating markets [87]. Compared with solvent-based, two component coatings, the water-based one can be expected to have limited pot life [71].

A new dispersion technology is used to make waterbourne PU coating with high solids, high gloss, excellent definition of image and long pot life - performance properties equal to the solvent-based systems, zero VOC and easy application. These performance advantages combined with the ability to tailor final coating properties through isocyanate selection, enable this system to be used in a wide variety of applications [88].

Core/shell type products with a polyacrylic component inside and PU shell provide excellent coating properties [89].

3.4.3.4 EP Coatings

EP resins had begun to displace other polymers from many applications, and the high-end property profiles inherent in this type of binder were considered indispensable if truly high performance, water-based coatings were to be produced. EP resins are also versatile, and lend themselves to the molecular engineering necessary to achieve water solubility and dispersibility [90].

There have been many adaptations of EP technology for water-based coatings, such as:

(a) Incorporation of emulsifiers in either or both the EP or amine package, permits addition of water during mixing.

(b) To use salts of amine functional resins.

(c) To use weakly acidic solvents such as nitro-alkanes able to form salts with amines. Salt groups stabilise EP-amine emulsions and allow the system to be reduced with water [71].

The use of waterbourne two component EP-amine systems is common today for civil engineering or maintenance applications that predominantly require curing at ambient temperature. These include coatings for concrete, and for metals especially anticorrosion primers for steel [91, 92].

3.4.3.5 Other Coatings

Poly(vinyl acetate) (PVAc) and vinyl acetate (VAc) copolymer coatings in latex form for buildings possess good light resistance, a medium stability to chemicals and low cost. VAc-methacrylate copolymers form good paints for interior and exterior application [54, 93].

Polychloroprene latices relatively new in the field provide a wide range of effective base polymers and modifiers from which to formulate useful environmentally friendly and cost effective coatings for a wide range of substrates [94, 95].

Fluoropolymers of different types are commercially available as coating resins [96]. Methods to fabricate perfluorinated coatings and films to impart the desirable properties of perfluorocarbons where they are most needed, without the disadvantages of handling and applying bulk perfluorinated materials are described in the literature [97].

One of waterbourne coating's performance drawbacks is that the technology has low peel and shear strength, according to the Pacific Northwest Pollution Prevention Resource Center (PPRC), a Seattle based non-profit organisation that provides information on pollution prevention. It has the ability to withstand wide temperature ranges, but has poor resistance to humidity.

Although it is not growing at the advanced rate predicted, use of waterbourne technologies are still on rise [98].

3.4.4 Curing Techniques

There are two stages in the drying of coating films:

(1) Removal of the solvent

(2) Fusion of polymer particles into a film, or crosslinking (curing), or a combination of fusion and crosslinking.

In lacquers, (1) is the only stage in the drying process. Fast air movement is even more important than heat for drying there. In 100% polymerisable coatings, only in stage (2)

is heating required - room temperature cure, convected hot air, jet-drying, radio-frequency, infra red, UV, electron beam radiation are used [99].

UV curing is a green technology and it has proven its value as a 'friend to the environment' in many ways, being VOC free. Running cost of UV in comparison to traditional thermal drying and curing are usually very favourable, with capital costs typically lower than installing catalytic converters or the emission control devices to existing thermal processes [100, 101].

Due to technical advances and increasing pressure to reduce VOC, use of UV curable water-based coatings are experiencing rapid growth in the market place especially for wood parts finishing.

Recent developments in the dispersion technology such as the technique of surfactant selection, the optimisation of various parameters in the dispersion process and the enhancement to dispersion stability have made it possible to disperse a variety of curable oligomers such as: acrylated EP, acrylated PU, acrylated polyester resins in water. Films based on the dispersions can have faster UV cure speed, better surface hardness and better flexibility compared with films based on undispersed resin systems [102]. UV curing offers many advantages including 100% solids with no solvents present in formulation and polymerisation is instantaneous leading to a large MW polymer [103].

UV curable systems were compared with electron beam (EB) radiation, which produces better surface curing and reduces the odour. EB curing is applied as surface technology today in various fields including the curing of coatings on panels for outdoor applications, lacquering of panels using the combined UV/EB curing processes, etc. [104].

In consideration of the intrinsic characteristics of the laser emission, these powerful light sources present many advantages which make them very attractive for curing applications. After absorbing a laser photon, the photoinitiator will split into radicals which will act on the monomer double bond, initiating in a fraction of millisecond the polymerisation that will develop in three-dimensions [105].

A novel penetrative cure at ambient temperature is based on the process in which, when a wet coating film reaches a thermoplastic state upon evaporation of liquid medium, is dipped in an aqueous solution of a crosslinking agent which penetrates into the film and cures it during the duration of dipping. This curing technology was applied to a cationic electrodeposition paint and the network formed into the film provided remarkable improvement in physical properties, water-resistance, solvent-resistance, weatherability and corrosion-resistance. The crosslinked surface layer prevented the penetration of corrosive material, and the underlying non crosslinked layer maintained sufficient adhesion between the film and the adherent [106].

Determining when the coating film is completely cured is very important. The standard methods are generally well accepted, but the data obtained are not always reproducible. A new method called evaporation rate analysis (ERA) is the most objective and reproducible [107].

3.4.5 Powder Coatings

Coatings made entirely from solid components are the result of the necessity to reduce solvent emission and energy consumption. Use of powder coating is undergoing a rapid growth especially in Europe and Japan. The general principle is to formulate a coating from solid components, melt mix them, disperse pigments and other insoluble additives in a polymer matrix, and pulverise the formulation. The powder is applied to a substrate, usually a metal (steel reinforcing bars) and fused to a continuous film by baking. More than 90% of the powder coating market is based on thermosetting polymers [54, 108].

Powder coatings present advantages such as: 100% solids, solvent-free, high application efficiency and high thickness and good film properties. Thickness of up to 500 μm can be achieved in a single application and the resultant coatings exhibit excellent film properties. But, they need specific automated equipment, colour ranges are difficult, higher temperatures are needed for flow/cure and they also present a risk of dust explosion [109].

The most used thermosetting resins for powder coatings are: EP (18%), acrylics (2%), unsaturated polyesters (28%), PU (7%), and hybrid systems (45%); and among thermoplastics, PA, polyolefins, PVC and poly vinyl fluoride are preferred [110, 111].

Through the use of additives, surface quality can be markedly improved and the overall performance profiles of powder coating systems can be fully optimised [112]. Addition of organic or mineral pigments of various colours and shades affects the UV curing performance of the powder coating. Photoinitiator type, pigment absorption, and particle size require careful consideration in formulating an opaque coating [113].

Exterior durable powders are generally used in either architectural applications like aluminium window frames, facades, or general applications like inside and outside coating of steel pipelines, coating of concrete reinforcing bars, gate, lamp posts, etc. [114].

Among the most used powder coating methods are: fluidised bed, electrostatic spray coating, electrostatic fluidised bed coating and flame spraying [110].

The disadvantages of this technology include the high capital cost for ovens and new spray equipment, high bake temperature that makes coating of large complex objects difficult, limited colour changeability, and no ability to modify formulation or film thickness during application [115].

Producers of medium density fibreboard for the building industry opt for powder coatings instead of vinyl and laminate films because of waste savings, the environmental advantage of eliminating VOC-containing lamination adhesives and the possibility of using only a one-step process and not a multi-step one like lamination [116].

3.4.6 Intumescent Coatings

Within fire protection of building materials, intumescent coatings are among the most widely used products with some unique features. They require a much lower thickness and weight than the alternative thermal insulating materials, and they allow simple application in thin films with high performance.

Intumescent means *'to swell up'* and intumescent coatings contain several active components that react as temperature increases to form a char to evolve gases and expand to more than 100 times its original volume [117, 118].

Although the use of intumescent combinations of a polyhydric organic compound, an acid foaming catalyst and a foaming agent have long been known to form fire protective coatings for combustible substrates, the incorporation of one or more of these additives into the basic polymer formulation to confer an intumescent property when exposed to flames is only a recent development. The type of polymer determines the necessary additives and their amount [119]. Salts of phosphoric acid like ammonium phosphate or ammonium polyphosphate which liberate the acid on which they are based at temperatures above 150 °C are nearly always used. Under the effect of heat, chloroparaffins, melamine and guanidine liberate large quantities of non-combustible gases such as ammonia, hydrogen chloride or carbon dioxide and ensure the formation of a carbonaceous foam layer over the substrate. The resin binder covers the foam with a skin which prevents the gases escaping.

Intumescent coatings are used for structural steel work or for other substrates such as timber, painted surfaces, and so on.

3.4.7 Durability of Coatings

Protection of materials is the most important role of coatings. The loss of protection effect can be produced by the paint degradation due to environmental factors and adhesion loss. The degradation produced by the weather includes the effect of the UV part of solar light, the penetration of oxygen, water, acidic pollutants from the atmosphere, and leads to successive deterioration stages such as: the loss of gloss, chalking, decrease of thickness

due to contraction, brittleness, crazing, peeling, etc. The final visible effect is cracking and flaking of the film.

The loss of adhesion is produced by the influence of microclimate and the water film on the adherent surface which leads to swelling, blister formation and cracking [120].

The major difference between geographical sites is the intensity of the environmental factors. It is anticipated that intense sunshine will accelerate breakdown of coatings, but the level of humidity (usually expressed in terms of rainfall) will also have a significant effect. Thus it is usual for sites to be compared in terms of the climatic conditions [96, 116, 121-123].

3.5 EPDM Membrane: Application in the Construction Industry for Roofing and Waterproofing

Bireswar Banerjee

3.5.1 Introduction

The elastomeric sheetings made out of butyl and polychloroprene rubbers were first introduced as barriers against water migration. In the early 1960s, EPDM rubbers were commercially available. Considering the superiority of EPDM-based membrane over other elastomers, its application to construction industry as moisture barrier was first introduced in the United States about 30 years ago.

EPDM sheeting has some high level properties which gives it dominance in many diverse applications [124]. These properties include: excellent weather resistance and almost maintenance free life expectancy of 20 to 30 years.

Waterproofing materials used in the construction industry must have the following essential characteristics:

(1) Impermeability to water,

(2) Good resilience,

(3) Resistance to oxidation, sunlight and ozone,

(4) Resistance to chemicals,

(5) Excellent dimensional stability, and

(6) Overall economy.

To meet these desirable properties, the appropriate polymer to consider would be ethylene – propylene-diene terpolymer (EPDM). In the manufacture of a cost effective, impermeable membrane system, EPDM rubber is the right choice as a discreet material for improved waterproofing and protective lining applications in roofing and other uses in the construction sectors [125].

3.5.2 Chemistry of the EPDM Elastomer

EPM - the saturated copolymer of ethylene and propylene is a non crystalline material with rubbery behaviour that gives excellent resistance to degradation, and requires peroxides for vulcanisation. EPM copolymer has brittle point in the range of –95 °C and it's T_g is –60 °C (**Figure 3.3**).

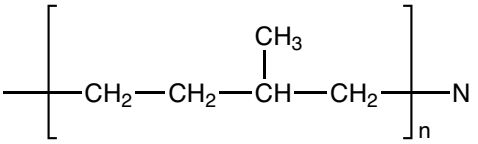
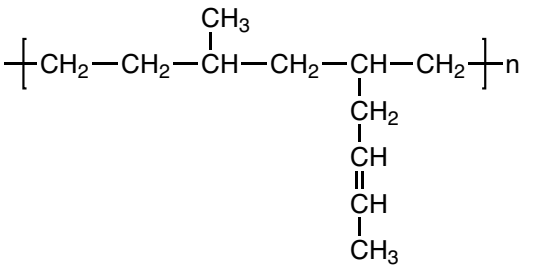


Figure 3.3 Structure of EPM

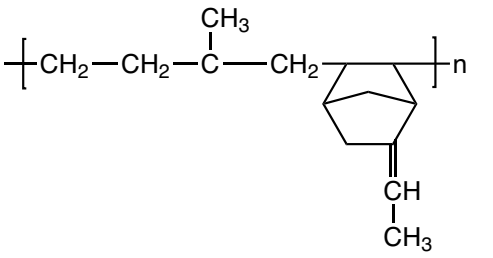
EPDM – is a terpolymer, polymerised from ethylene, propylene and a small percentage of diene (the latter provides unsaturation in the side chain or pendent to give sites for crosslinking) which can be vulcanised by a conventional process with sulfur and it provides excellent weather resistant properties to the vulcanisates. Applications are in the temperature range of 150-175 °C with the properties of very low compression set - peroxide curing may be necessary in place of sulfur. In commercial EPDM usually 4-5% by weight of diene and 30-70% by weight of ethylene are used to get a serviceable product. Among the natural and synthetic elastomers available, ethylene/propylene rubber has the lowest specific gravity [126].

Rubbers with a high proportion of ethylene or propylene offer higher tensile strength and elongation properties. By increasing the ethylene content the ultimate product shows higher hardness, high modulus, increased tensile strength and also enhanced rebound resilience of the vulcanisate. EPDM rubber shows no degradation in tensile strength up to 125 °C when aged for 1500 hours.

Commercial dienes used for EPDM are 1,4 hexadiene (**Figure 3.4**), dicyclopentadiene (DCPD) and ethylidene norbornene (ENB) (**Figure 3.4**).



Ethylene propylene 1,4 hexadiene



EPDM with ENB

Figures 3.4 Ethylene propylene 1,4 hexadiene and EPDM with ENB

Use of DCPD results in the slowest curing for EPDM, and adding 1,4 hexadiene offers an intermediate rate of cure, whereas ENB creates fastest curing rates, as shown in **Table 3.2** [127].

Table 3.2 Effect of curing rate on the diene monomer in EPDM polymerisation

Diene	Rate of cure
DCPD	Slow
1-4 Hexadiene	Intermediate
ENB	Fast

A wide variety of EPDM are available with varying degrees of Mooney viscosity, MW, ethylene/propylene ratio and with different cure rates as mentioned previously.

EPDM rubber is an important, versatile, commercial material, highly extendible, allowing use of high levels of filler and plasticisers in the compound but still maintains good physical properties. In the manufacture of inexpensive functional products, use of this elastomer gives distinctness because of its low specific gravity and high extendibility. Manufacturing recipe for water and weather proof membrane is given in **Table 3.3** and the properties in **Table 3.4** [128].

Table 3.3 Manufacturing formulations for EPDM membrane (phr)	
EPDM (MED ENB)	**100.0**
Zinc oxide	5.0
Stearic acid	1.0
Antioxidant: TMQ	1.5
Antiozonant: DTPD	0. 5
FEF black	60.0
SRF black	40.0
Naphthenic oil	75.0
MBT	1.0
TMTDS	0.8
Tetrone A	0.8
Sulfur	2.0
Med ENB: Medium ethylidene norbornene TMQ: Polymerised 2,2, 4-trimethyl-1, 2-dihydroquinoline DTPD: *N*′,*N*-diaryl-paraphenylene diamine FEF: Fast extrusion furnace SRF: Semi-reinforcing furnace MBT: 2-Mercapto benzothiazole TMTDS: Tetramethyl thiuram disulfide Tetrone A: Dipentamethylene thiuram tetrasulfide	

Table 3.4 Properties of EPDM after Mooney scorch at 130 °C for 12 minutes	
(a) Cured at 160 °C for 10 minutes	
Tensile strength	10 MPa
Elongation at break	300%
Hardness	60 IRHD
Tear strength	20 N/mm
(b) Aged at 80 °C for 28 days	
Change in TS	20%
Change in elongation at break	40%
IRHD: International Rubber Hardness Degrees TS: Tensile strength	

3.5.3 Process of Manufacture of EPDM Membrane

The first step of manufacturing a membrane is to prepare a suitable rubber compound either in a Banbury internal mixer or in an open two roll mixing mill by adding different compounding ingredients in the proper sequence during the mixing operation to get a well dispersed compound.

Sheeting can be made by calendering or extrusion processes from the compound prepared as in **Table 3.3**. The viscosity of the rubber compound is required to be checked before further processing.

3.5.3.1 Calendering

To manufacture EPDM sheeting/membrane, pre-warmed, plasticised EPDM compound at a temperature of 80-100 °C is used for calendering in a 3 roll in-line 'I' configuration rubber calender machine or in a 4 bowl 'Z' configuration rubber calender machine.

Strips or dollies of EPDM rubber compound of maintained viscosity can be fed to the first roll nip of a 3 bowl calendar. The thickness of the sheeting is adjusted by operating the motorised roll nip adjustment device fitted on the machine.

The first nip of the calender machine produces the sheet which is then fed round to a second nip thus precision control of the sheet gauge is obtained. Using the second nip blistering due to air entrapment can also be avoided. Membrane of the desired thickness comes out from the machine in a continuous length, and is then wound-up on the opposite side of the machine at uniform speed. A textile liner can be used to prevent sticking of the sheeting with the help of a let-off roll. A suitable dusting agent like starch powder/talcum powder may also be dusted on the membrane in place of liner as an anti-sticking agent.

In an inverted L and Z configuration four roll calender machine, two thin layered sheets can be prepared in the first and third nips. Taking out the two thin sheets and plying up with two rubber covered rolls pressure device just before the winding operation, a single ply sheet is formed. This system can be adopted for higher thickness sheeting and to help in eliminating the blistering problem of the membrane. The quality of the sheeting depends on the speed of the machine and proper temperature control of the rolls [129].

3.5.3.2 Extrusion Process

EPDM rubber sheet can also be made using the hot or cold feed rubber extruder machine of 20-30 cm screw diameter. For a hot feed machine the L/D ratio of the screw should be 5:1 and for the cold feed extruder 20:1.

The technique of producing a sheet by an extruder is to extrude a higher diameter tube. The temperature of the compound needs to be maintained in the range of 95-110 °C to get better extrusion properties.

A sharp cutting tip is fitted at the extruder die head which slits the tubular section of the tube on one side and opens up to form a flat sheet. Extruded sheet is then cooled by passing it through a cold water tunnel, and after drying and winding onto batch rolls, it is dusted with a dusting agent like starch/talc powder to prevent sticking during vulcanisation. Curing can be done in an autoclave in batches. The advantage of using the extrusion process is that it reduces the chance of blistering of the sheeting.

3.5.4 Process of Preparation of Adhesive

The rubber is broken down in an open two roll mill for five minutes. Subsequently magnesium oxide and antioxidant, and lastly zinc oxide are added to the mix as in the formula given in **Table 3.5** [130].

Table 3.5 Polychloroprene based contact adhesive for EPDM membrane installation (phr)

Polychloroprene rubber (Neoprene AC)	**100**
Light magnesium oxide	5
Zinc oxide	5
Antioxidant: naphthylamine antioxidant	1
Heat–reactive tertiary butyl phenolic resin	30
Terpene phenolic resin	20
Hexane	250
Acetone	150
Tolune	200
Solid content	26%

The milled stock is then cut into small pieces and swelled in solvent for 24 hours. Swollen stock can be fed into a rubber solution churner (a motorised, vertical, rubber solution mixer), and solutions of resins in solvents are prepared separately and are added gradually to the feedstock for proper dispersion of the ingredients. Finally the balance blended solvent is added in to the churner. The machine is run for a desired period to get a rubber solution of consistent and desired viscosity.

3.5.5 EPDM Polymer Characteristics of Crack Resistance

EPDM is totally resistant to ozone, heat, water and UV radiation. The architects and building contractors in USA and Japan have proved how dependable this material is. A lot of flat roofs (more than 55%) are covered with EPDM sheets in these countries because of the superiority of this amazing material over conventional waterproofing substances.

EPDM rubber sheet can be stretched up to 400% – it will not tear, crack or split but returns to its original position, shows unfailing flexibility. Because of these outstanding properties EPDM rubber-based membranes have many applications, which include the following [125]:

(a) waterproofing of roofs
(b) wall and foundation waterproofing
(c) waterproofing of underground constructions
(d) walkway coverings
(e) parking and plaza deck flooring
(f) fluid storage lining
(g) lining for irrigation canals
(h) landscape ponds lining
(i) dams for waterways
(j) lining of effluent treatment tanks

3.5.6 Distinctive Waterproofing Properties of EPDM Membrane

A reliable roof is the most important part of a building and it is this which decides the quality and ultimate life of a building. An efficient roof sheeting should never allow even traces of water to pass through it at any given point and should maintain this characteristic over a long period of time. It should withstand slight movements of the structure, bad weather, chemical degradation and mechanical stresses and strain.

EPDM rubber-based membrane can meet the stringent requirements to prevent water seepage on roof tops, vertical walls, ground and basement walls in construction applications.

Over time it is far more economical than traditional waterproofing systems. A single layer membrane of thickness of 1.2 mm made from EPDM rubber provides superior waterproofness than multi-layer traditional material systems.

EPDM membrane of 1.2 mm thickness is 22 times more waterproof than asphalt and 59 times as waterproof as PVC sheet.

3.5.7 Maintenance Free, Temperature Endured Roof Sheathings

EPDM roof sheet is one of the lightest roof membrane materials because of its low specific gravity. It is highly suitable for lightweight structures and puts negligible extra load on the roof to be waterproofed. It is serviceable over a wide range of temperatures –50 °C to 150 °C, and the membrane does not embrittle in freezing condition nor soften in hot weather.

In many countries asphalt felt coating is used to protect the building roof from leaking – the life of such a waterproofing system is only two to three years. For exceptional water and weather resistance the EPDM roof membrane is known to be serviceable for more than 20 years and virtually no maintenance is required.

Comparative properties of different waterproofing materials are shown in **Table 3.6**

Table 3.6 Comparative properties of EPDM membrane *versus* other materials

Properties	EPDM	Butyl	Poly-chloro-prene	PVC	PU	Modified bitumen	Bituminous build-up roofing
Dimensional stability	E	G	G	F	F	F	F
Resistance to:							
High temperature	E	G	F	P	F	P	P
Ozone	E	G	G	G	G	F	F
UV	E	G	G	F	G	F	G
Cold cracking	E	G	F	F	F	P	P
Weather	E	G	G	F	F	P	P
Acids and alkalies	E	G	E	G	F	NA	NA
Cost effectiveness	Less expensive	Very expensive	Very expensive	Expensive	Very expensive	Expensive	Expensive

E: Excellent
G: Good
F: Fair
P: Poor

3.5.8 Installation Engineering of EPDM Membrane

EPDM membranes can be factory assembled from smaller width sheets by a hot vulcanising process, using suitable rubber-based adhesive or room temperature vulcanisable adhesive system, to form a higher width waterproof joint surface. Alternately, the individual sheets can be welded at site with the help of a proper adhesive system.

As the EPDM membrane is elastic and tear resistant at low temperatures, the sheets can be manipulated over pipes and curves in any weather and can also be fitted properly around projections.

For use on roofs, the surface of the roof or the substrate must be clean, free from debris, chipping or other materials prior to the laying of the built in sheet is necessary. If the surface is rough or uneven, an appropriate board sheet material can be used to provide a smooth surface.

The following methods can be used for installation engineering of EPDM membrane:

(i) ballasting
(ii) adhesive bonding
(iii) mechanical fixing

3.5.8.1 Ballasting

Ballasting is an economical and quick system to secure an EPDM roof membrane. Waterproofing sheet is simply fitted over the flat roof or to a low slope, and covered with cleanly washed well rounded gravel with a diameter of 40-50 mm. Corners may be ballasted with suitable concrete slabs to prevent the sheeting from wind uplift and the perimeter can be fixed with contact adhesive.

3.5.8.2 Adhesive Bonding

Bonding EPDM membrane with a cold adhesive is appropriate when structures are too light or roofs are steep with curves or sharp corners. Before application of the adhesive, the surface should be made smooth, clean, free from dust, oil, grease or other contaminates which may affect the adherence. This method is economical to cover all types of complex structures even on vertical walls. The sheets can be adhered to smooth surfaces of cement concrete, wood and metallic surfaces made of steel, aluminium, etc. An adhesive bonding system is also suitable for use on rigid insulation and old concrete roofing.

The cold bonded rubber-based adhesive is applied to the area to be covered by brushing or spraying on the surface of the floor, roof or wall, and to the contact surface of the membrane before laying for better adherence. Applying pressure with a metallic/rubber covered roller can help to remove undersurface trapped air and will allow proper contact of the membrane and the surface.

3.5.8.3 Mechanical Fixing

To anchor the sheet mechanically, non-penetrating rivets are used to fix the membrane, particularly on sloped roofs or steep surfaces. Polyamide studs are fixed to the deck with an EPDM rubber cap and metal clip. Spacing of the studs depending on the expected wind lift, and the covering is then placed over the fixed studs. With the help of proper lubricants, caps are secured to the studs with a fastener tool and the perimeters can be secured with adhesive.

3.5.9 Effluent Treatment Plant Lining

The significant characteristics of EPDM sheeting, such as, its resistance to acids and alkalies, resistance to vegetable and animal fat, being unaffected by toxic chemicals, and with good mechanical properties make its way as an effective lining barrier for effluent treatment plants.

3.5.10 Ecological and Decorative Gardening Applications

Ecological and functional designed roof tops and terrace gardening become more and more popular to improve the working and living environment. Because of the unique advantages to prevent plant root penetration, resistance to rot, fungi, algae and micro-organisms, EPDM membrane considered to be the most suitable material as an effective waterproof liner for building and landscape decoration.

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4 Systems for Condensation Control

Arnold Janssens

4.1 Introduction

In building components, such as walls and roofs, plastics are most often used in the form of films or sheets. These films contribute to moisture control of the building envelope, by improving the air tightness, reducing the migration of water vapour from the inside environment, or preventing rain penetration. Depending on the control function of the plastic film, it is referred to as the air barrier, the wind barrier, the vapour retarder or the weather-resistive barrier.

This chapter gives a review of the use of plastics for condensation control in building components. The evolution of condensation assessment methods and control strategies developed by building scientists are compared to the condensation control measures and materials applied in building regulations and practice. This overview helps in defining performance criteria for the use of plastic films in building components.

4.2 Standard Condensation Control

4.2.1 Standard Assessment Methods

Conventional condensation control strategies focus on the control of water vapour migrating into the building envelope by diffusion under vapour pressure differences. Two control measures are common practice. The introduction of a vapour retarder at the warm side of the building envelope restricts the entry of water vapour into the construction. The application of a ventilated cavity may facilitate the escape of water vapour to the cold side of the construction. The conventional moisture performance analysis consists of defining the proper vapour retarder or the required ventilation area, using analytical calculation tools or rules of thumb. These control measures and calculation methods are the subject of various standards and guidelines in Western Europe [1-4]. Also in North America, vapour retarders and ventilation are an element of almost all building codes [5].

Most of the guidelines and standards on condensation control in Anglo-Saxon countries go back to the studies on moisture accumulation in residential woodframe walls and

roofs performed by Rowley in the 1930s [6]. In his experiments he demonstrated the general principles for condensation control within insulated constructions: to reduce the rate at which water vapour can enter a construction on the side of higher temperature, and to enhance its escape on the side of lower temperature. Rowley developed a qualitative assessment method for condensation, later called the dew-point method. His recommendations were for the use of vapour retarders and vented air spaces.

The condensation control standards of the European continent are all based on the calculation method developed during the 1950s by Glaser, generally known as 'Glaser's method' [7, 8]. The method differs from the dew-point method by its better physical and mathematical basis. It allows quantification of the condensation rates and locations in a multi-layered assembly exposed to a temperature and vapour pressure gradient. It was originally developed to predict condensation in a sandwich construction for cold storage walls, but later it was applied to all types of building assemblies, mainly as a result of the influence of German publications. In the 1970s, the method evolved to a more appropriate condensation evaluation tool with the introduction of realistic boundary conditions, better assessment criteria and the concepts of equilibrium state and critical moisture content [9, 10]. In the 1980s, the method was integrated into computer models with the possibility of studying the drying of construction moisture. However, the basic assumptions of all methods were the same:

(1) moisture migration in and out of the envelope is by water vapour diffusion,

(2) the boundary conditions are steady-state, and,

(3) all heat and vapour transport is one-dimensional, i.e., perpendicular to the envelope.

The standards differ in the way the environmental conditions are treated and in the way the calculation results are assessed. In the most simple case, the condensation rates are calculated for a 60 day winter period with constant extreme internal and external temperature and humidity [2, 4]. The designer is advised to use his practical experience to assess the calculation results. In the more elaborate guidelines the outdoor climate is described by a moisture reference year with monthly mean values of humidity and temperature, corrected for solar radiation, clear sky radiation and the non-linear relationship between temperature and saturation humidity [1, 3]. The indoor conditions are selected from a set of internal climate classes, to account for the expected building use and vapour production. The envelope moisture performance, predicted by a calculation for every month of the year, is assessed using two criteria: the annual moisture balance and the maximum amount of accumulated moisture. The envelope design is rejected if there is a net moisture accumulation over the year, which means that the total condensation amount during winter is not balanced by drying in summer. The maximum calculated moisture accumulation may be compared to tabulated values in order to judge the design for the degradation of material durability and thermal resistance.

The standards [4] also include rules for the design of ventilated cavities. These design rules are based on analytical calculation methods developed to predict the potential of cavity ventilation for condensation control [11].

The basic assumptions of these methods are almost the same as with Glaser's method:

(1) moisture migration from the indoor environment into the envelope is by water vapour diffusion,

(2) the boundary conditions are steady-state,

(3) all heat and vapour transport is perpendicular to the envelope, except cavity ventilation, and,

(4) air flow is possible along the cavity only.

4.2.2 Standard Condensation Control in Building Practice

The principles and measures of condensation control described in scientific reports and applied in the standards have found their way to building industry, designers, contractors and builders through a variety of technical recommendations and commercial publications. Design guidelines may vary from country to country, and range from simple to more differentiated.

The Belgian Building Research Institute (BBRI) for example has catalogued various reference designs for insulated roofs with a sound moisture performance, and has defined the applicability of the designs according to the indoor climate of the building and the vapour transfer properties of the roof composing materials [12]. The German standard on the other hand lists design rules for the required ventilation area, cavity width and vapour retarder properties for roofs, regardless of the humidity in the building and the roof construction. Examples of these rules are given in **Table 4.1**. According to an enquiry on regulations and moisture control practices in different countries, the German standard has been used as a reference in the building industry in Central and Western Europe [13]. Consequently in European building practice the attitude exists that the simple rules of thumb for vapour retarders and ventilated cavities are generally valid and the only issues in condensation control. **Figure 4.1** illustrates the application of the standard condensation control in tiled roof construction.

The most commonly applied vapour retarder materials in lightweight envelope parts are polyethylene film and bituminous or aluminium kraftpaper. In flat membrane roofs, the bituminous membranes applied for water-tightness are also used as a vapour retarder. A new

Table 4.1 Standard condensation control in roofs (after [4])			
Roof slope	**Cavity width, cm**	**Ventilation area**	**Diffusion thickness of the layers at inside of cavity, m**
≥ 10°	0	0 cm^2	≥100
	2	eave: a ≥ 20 cm^2/m* with minimum 200 cm^2/m ridge: a ≥ 10 cm^2/m	a ≤ 10: ≥ 2 a ≤ 15: ≥ 5 a > 15: ≥ 10
< 10°	0	0 cm^2	≥ 100
	5	eave: a ≥ 20 cm^2/m	≥ 10
*a = *eaves to ridge length of roof face (m)*			

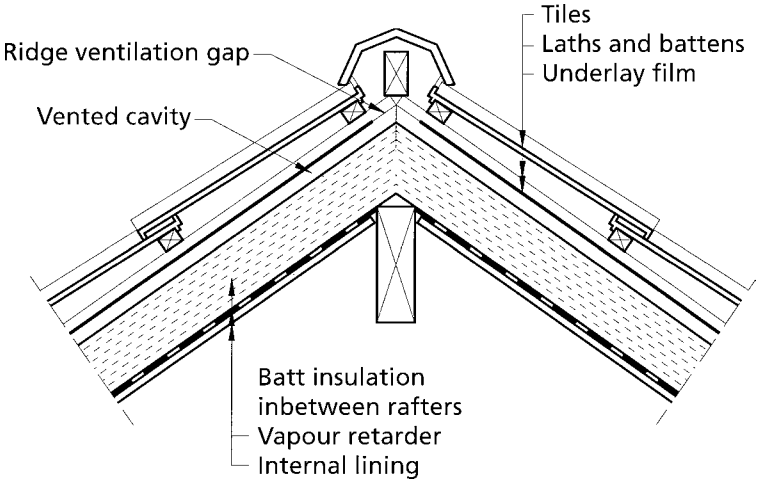

Figure 4.1 Ridge detail for tiled vented roof design, according to standard condensation control practice.

generation of vapour retarder materials are the so-called moisture-adaptive sheets, developed for specific applications. One example is the hygro-diode membrane, originally conceived by Korsgaard [14] as a water permeable vapour retarder to be used in flat, cold deck roofs. The membrane consists of a synthetic felt with good capillary properties, sandwiched between staggered strips of polyethylene. The felt wicks excess (liquid) water from the building envelope, while the plastic strips retard vapour migration into the roof. Another example is the 'humidity

Table 4.2 Vapour retarder classes [12]		
Class	**Diffusion thickness**	**Materials**
1	2 m < μd ≤ 5 m	Kraftpaper, bituminous felt, polyethylene film (d < 0.2 mm), polyamide film (at RH < 50%)
2	5 m < μd ≤ 25 m	Polyethylene film (d e 0.2 mm), hygrodiode membrane (at RH < 50%)
3	25 m < μd ≤ 200 m	Bituminous membranes (d > 3 mm)
4	μd > 200 m	Bituminous membranes with metallic foil reinforcement, multi-layer membranes
RH: Relative Humidity *μd: equivalent air layer thickness*		

controlled' vapour retarder, developed by Künzel [15] for moisture control in historic facades retrofitted with thermal insulation on the inside. The system consists of a polyamide film, engineered such that the vapour resistance is high when exposed to humidities typical for the indoor environment during winter, and low when exposed to humidities typical for indoor summer conditions. This way the film prevents moisture accumulation during cold weather, without reducing the drying capacity during summer.

In the Belgian design guides, four vapour retarding classes have been developed, depending on the resistance to water vapour diffusion of a vapour retarder (expressed as the diffusion thickness or equivalent air layer thickness: μd). **Table 4.2** gives the boundaries of the vapour retarding classes, and some examples of materials.

4.3 Controlling Air Leakage

4.3.1 Moisture Accumulation Due to Air Leakage

The importance of air leakage for the moisture performance of building envelopes was first studied and recognised in countries with a building tradition of insulated lightweight construction, such as Canada and Scandinavia. The Division of Building Research at the National Research Council of Canada was probably the first research institute to focus on air leakage as an essential element in moisture control. This notion grew primarily by the observation of moisture problems exhibited by buildings in the cold Canadian climate. In the 1950s, Hutcheon [16] concluded there had to be another mechanism for vapour migration than the usual one of vapour diffusion, to explain the observed rates of moisture

accumulation in the building envelope. At a symposium in 1965 the Canadian researchers presented contributions on the effects of air leakage. Wilson and Garden [17] discussed the driving forces inducing air movement in buildings as the result of building chimney action (thermal stack effect), wind action and imbalance of mechanical supply and exhaust ventilation systems. They showed the potential for moisture accumulation due to air leakage to be two or more orders of magnitude higher than that due to diffusion, depending on building and climate. They concluded that moisture problems due to exfiltration of warm, moist air generally increase with increasing building height, decreasing average winter temperatures and increasing building humidity. Dickens and Hutcheon [18] recommended airtightness of the internal linings as a first line of defense against moisture problems. The common vapour retarder should block air flow in order to be effective. They achieved this by sealing the vapour retarder at all joints and at the edges of openings, contrary to Canadian practice at the time. Finally they advised that cavity ventilation as a condensation control measure should be avoided, in order to minimise air leakage where a good seal at the inside of the envelope was not obtained. They also showed that actual ventilation rates in cavities vary widely depending on local pressure patterns around buildings and that the vapour capacity of cold ventilation air is often too small to control condensation effectively.

After the energy crisis in the 1970s the application of thermal insulation materials in buildings increased. As a result, moisture problems in lightweight insulated envelope parts were also experienced and studied in countries with moderate climates. Many of the building researchers in the United States and Western Europe adopted similar conclusions and recommendations as were recommended earlier for cold climates [19-22].

A typical example of the evolution of the principles of condensation control among building scientists is found in the ASHRAE Handbook series. *The Handbook of Fundamentals* [23] is a basic reference for mechanical and building engineers, with upgraded issues every four years. In the 1960s and 1970s the Handbook stressed the use of vapour barriers and ventilation of structural cavities as major condensation control measures. The 1981 edition recognised airbourne vapour movement to be far more powerful in transporting water vapour within the building envelope than water vapour diffusion. In a new paragraph on the importance of air leakage, airtight construction was called the first defence against interstitial condensation. More importantly from a psychological point of view, the terminology for 'vapour barrier' was abandoned in favour of the physically more correct 'vapour retarder'. Since the 1993 issue, the Handbook includes a section on air barrier functions and properties.

While the identification of air leakage as a source of moisture problems is half a century old, the prediction of its effects is more recent. During the past decade the understanding of the moisture performance of building envelopes has increased with the development of powerful computer models. Hens [24] gave an extensive survey of the state-of-the-art of heat, air and

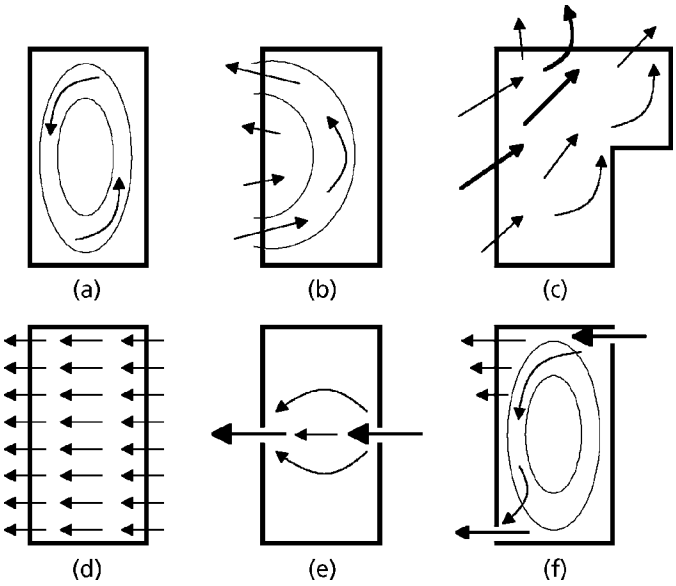

Figure 4.2 Typical air flow patterns in insulated cavities: (a) air rotation by natural convection, (b) air infiltration by natural or forced (wind) convection, (c) wind-washing around corner, (d) diffuse air leakage, (e) air leakage through gaps and (f) mixed pattern (after Ojanen and Kohonen [29]).

moisture (HAM) models for building components. The early methods to calculate moisture accumulation due to air leakage were analytical [25] or based on hydraulic network analysis [26]. Most of the recent computer models use numerical finite difference techniques to predict the transient hygrothermal behaviour of multilayer assemblies in one or two dimensions [27]. The computation results show the complex interaction of the transport and storage processes of heat, air and moisture in building components. The moisture accumulation due to air leakage appears to vary substantially depending on the building design, the indoor and outdoor climate conditions, the moisture transfer and storage properties of building materials and the actual air flow patterns through the envelope. Numerical HAM-calculations have been applied recently to develop design guidelines for air barriers [28].

4.3.2 Thermal Effects of Air Movement

An additional reason for controlling air movement in the building envelope is the effect of air flows on the energy efficiency of buildings. Many researchers in building and thermal insulation engineering have studied the mechanisms of convection heat transfer.

Air movement influences the thermal performance of building envelopes in various ways: by natural air convection in and around the thermal insulation layer, by air leakage through the envelope or by forced air infiltration in the thermal insulation (so-called wind-washing). **Figure 4.2** gives a classification of the various air flow patterns. Two configurations have been studied in detail by building researchers: a cavity filled with an open porous insulation material [30] and an air cavity partly filled with a thermal insulation layer [31]. Because of the high possibility of workmanship errors in building envelope applications, the sensitivity of the thermal performance to defects in the insulation layer has often been a topic [32]. Furthermore Timusk and co-workers [33], and Uvsløkk [34] have made measurements that showed the significant thermal effects of wind in insulated timber framed constructions, especially at exterior corners.

In general, the studies indicate that air movement may substantially decrease the energy efficiency of building envelopes, even at small flow rates. The recommendations to preserve the effectiveness of thermal insulation are for airtight construction, elimination of air gaps at either side of the insulation layer and protection of the insulation cavity against air infiltration. To achieve this the thermal insulation layer should fill the structural cavity completely and be protected from the wind by a so-called wind barrier. This concept is called the 'compact' or 'sandwich' envelope design by Hens [21] and Künzel [22]. Air leakage criteria for wind barriers in wood frame walls are given by Ojanen [35] and Uvsløkk [34]. They are based on calculations and experiments in order to limit the relative increase in heat loss by wind-washing to less than 5%.

Table 4.3 lists examples of wind barrier performance criteria.

Table 4.3 Air leakage criteria after Di Lenardo and co-workers [28] and Uvsløkk [34]

Application	Air leakage, $m^3/m^2/h$ (75 Pa)	Air permeance, $m^3/m^2/s/Pa$	Diffusion thickness wind barrier, m
Air barrier material	< 0.07	$< 0.3 \times 10^{-6}$*	
Air barrier system	< 0.72	$< 2.7 \times 10^{-6}$*	< 0.25
+ joints	< 0.18	$< 0.7 \times 10^{-6}$*	> 3.25
Wind barrier + joints	< 3.75*	$< 14.0 \times 10^{-6}$	

**Extrapolation based on linear flow-pressure relation.*

Since wind barriers are located at the cold side of the thermal insulation (in cold climates) they should combine a sufficient air and water tightness with a high vapour permeance. Materials which combine these properties and are often recommended as wind barriers are the spunbonded plastic films (also called house-wraps). These films are composed of rolled synthetic filaments (typically polypropylene or polyethylene fibres) that are welded together to form a continuous porous fabric. Measuring procedures and results of vapour transfer properties of spunbonded plastic films are reported in detail by Janssens and Hens [36]. The diffusion thicknesses of the films are a few centimetres and of the same order of magnitude as an air boundary layer.

4.3.3 Air Barrier Systems and Requirements: The Canadian Example

By the end of the 1970s, building research efforts in Canada concentrated no longer on the effects but on the control of air leakage. Handegord [37] left no doubt about the challenges for construction practice to achieve improved building performance: 'Specifications that simply call for a continuous air or vapour barrier are not likely to achieve air-tightness in actual construction'. He pointed out that the development of practical details, changes in building practice and construction sequence, and performance evaluation were essential steps to achieve air leakage control in building practice. A research programme was carried out in order to define requirements for air-tightness, and to establish testing and evaluation procedures for air barrier systems. This work resulted in the incorporation of prescriptive requirements for air-tightness in the National Building Code of Canada, and in the development and official registration of adequate air barrier systems, in order to enforce air-tightness of building assemblies in practice [38].

An air barrier system is defined as a combination of materials within wall and roof assemblies which establishes a continuous plane of air-tightness in the building envelope. Its most important function is moisture control, but it also plays a significant role in energy efficiency, rain control and external noise protection. Essentially the system has to meet four requirements: a sufficiently low air permeance, continuity at all joints and intersections, strength against peak wind pressures, and the ability to meet these functions over the service life of the system (durability). These criteria apply to all air barrier components: boards, films, fasteners, gaskets, sealants. Additional points to be considered in the design and assembly of air barrier systems are the accessibility for maintenance and the certification of specialised trades, in order to ensure that in practice air barrier systems are installed at a consistent quality.

Upper limits for the air permeance of air barrier systems, including anticipated joints and penetrations, are prescribed by Di Lenardo and co-workers [28] as a function of the

water vapour permeance of the materials at the cold side of the thermal insulation. They are based on computer simulations of the moisture accumulation in timber frame walls. The maximum allowable air leakage rates are defined considering both moisture collection and energy conservation. Even when air leakage does not result in moisture accumulation, the value of 2.7×10^{-6} $m^3/m^2/s/Pa$, is considered to be the maximum allowable air permeance of the system. This upper limit is necessary to limit the heat loss due to air leakage to 15% of the conductive heat transfer through an insulated wall. Examples of air barrier requirements are listed in **Table 4.3**.

4.3.4 Air Leakage Control in Building Practice

Several handbooks and design guidelines on moisture control in North America have adopted requirements, descriptions and construction details for airtightness [39, 40]. Resistance to air leakage can be provided at any location in a building assembly, each location having its pros and cons. Most guidelines however recommend applying the air barrier system at the warm side or inside of the thermal insulation, in order to eliminate all flows of humid air to the colder side of the thermal insulation. The air barrier system is adapted into conventional building construction by using existing envelope components and addressing continuity at critical locations. Two approaches are common in residential lightweight construction. Either a plastic vapour retarder film, often polyethylene, is used as the air barrier material (then called the air-vapour barrier), or the internal lining, generally a gypsum board, is designed and assembled to resist air leakage.

Continuity is achieved at construction joints, intersections and penetrations, using tape, gaskets, sealant or glue between the air barrier materials, framing elements and plastic accessories. Long-term field studies have demonstrated that both approaches are capable of meeting building air-tightness requirements in practice [41].

The implication of the concepts of air flow control for wood frame roof design is illustrated in **Figure 4.3**.

Recent design guidelines in Western Europe also provide recommendations for airtight construction in order to control condensation and heat loss in building components [42]. Air-tightness of the building envelope is considered to be a prerequisite for the validity of standard condensation assessment methods. However, contrary to the Canadian guidelines, no performance requirements for air barrier systems are established. In addition, for many architects and contractors in Western Europe the concepts of air-tightness are new and difficult to understand. They have a tradition of heavyweight construction (masonry walls, concrete floors) for which air-tightness was

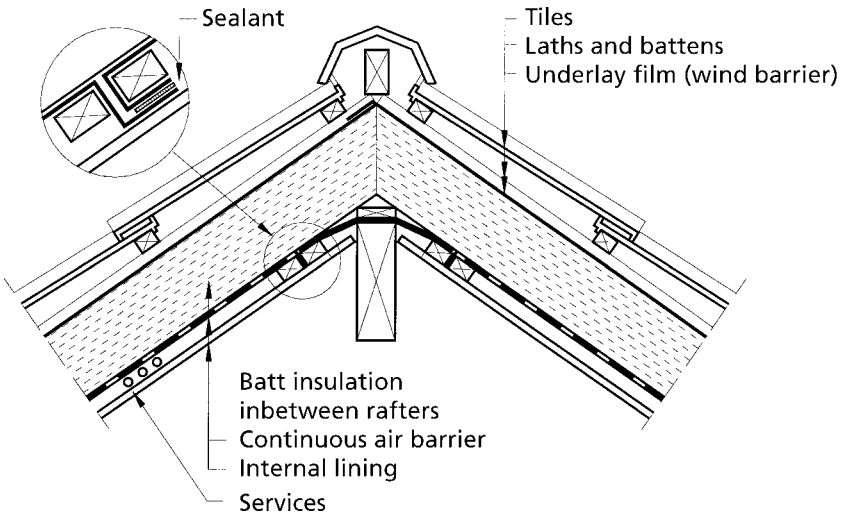

Figure 4.3 Ridge detail for tiled compact roof design, according to the concepts of air leakage control

never a concern. At the moment the expertise and quality of care needed to design and install a well-performing air barrier is lacking, despite the existence of design guidelines and the development of air barrier systems by the industry. As a result lightweight building assemblies remain sensitive to air leakage through the joints, cracks and perforations, common to most existing methods of construction.

4.4 A Systems Approach to Condensation Control

4.4.1 Warm Roof Designs

For some specific envelope designs it is recognised that neither the standard condensation control measures nor the use of an interior air barrier system are reliable measures to prevent moisture problems in practice. After experience of premature failures, the envelope design is often changed pragmatically. For example, in Belgium, the use of cavity insulated wood frame membrane roofs, so called cold deck roofs, was abandoned in favour of the warm deck roofs with air-vapour barrier, thermal insulation and roofing membrane located on top of the roof deck [43]. Also in severe climates new envelope designs and construction methods have been introduced. In the Canadian Northwest Territories, a similar design assembly is preferred for wood-frame roofs, walls and floors: the 'overcoat approach'

implying the location of the air-vapour barrier, the insulation and the exterior finish outside of the structural sheathing and framing. Messer [44] and Ogle and O'Connor [45] proposed a warm roof and wall design to control condensation in non-residential Canadian construction. The implication of this approach for wood frame roof design is illustrated in **Figure 4.4**.

There are two major reasons for these changes in envelope design. First continuity of the air-vapour barrier is easier to achieve and less susceptible to damage. Due to its location on the outside of the structure, interference in continuity by major structural elements, internal walls and service penetrations is minimised. The continuity of airtightness is less affected by other trade's work, such as electricians or plumbers. Because the air barrier is applied to a rigid support, it is easier to install correctly. Moreover, due to the inverse construction sequence, the air barrier has to provide a weatherproof enclosure at an early stage in construction, as a result of which the care of designers and contractors to achieve continuity increases. Secondly, the potential condensation planes are shifted to the outside of the structural cavity, so that condensation, if occurring, causes less damage. An additional benefit is the eliminated thermal bridging through the structural framing. Disadvantages are, of course, the higher initial cost and thickness of the new design and the possible technical difficulties to connect the insulation and the exterior finish to the structure.

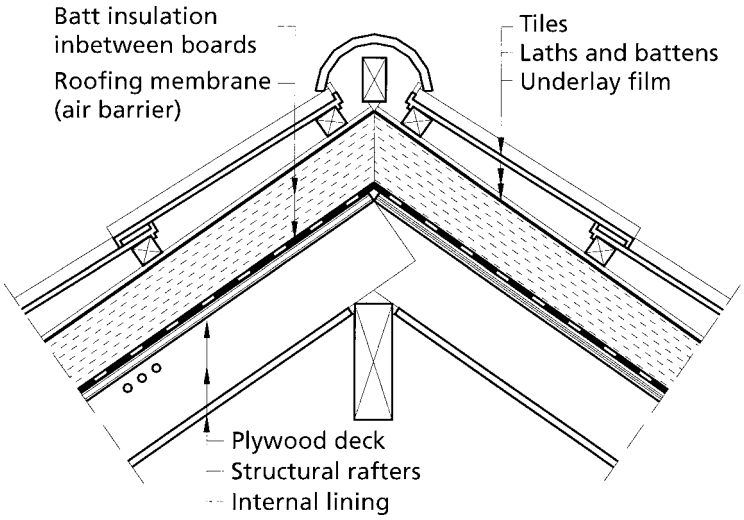

Figure 4.4 Ridge detail for tiled warm roof design

4.4.2 Condensation Control Systems

As illustrated by the previous example, other factors than purely physical considerations play an important role in condensation control. The properties of air barriers or vapour retarders are not the only concerns in preventing condensation problems. Different condensation control strategies may be combined in order to create condensation control systems with a greater probability of effectiveness in building practice.

Ten Wolde and Rose [46] presented two major approaches to moisture control in the building envelope. The first is to design and construct the building envelope for a high tolerance for moisture. The second is to limit the moisture load on the envelope. Designing the envelope for a high moisture tolerance implies the use of measures to control the migration of moisture into the construction, to control moisture accumulation in building materials or to enhance removal of moisture from the building assembly [40]. The limitation of the moisture load often involves control strategies on the level of building design and operation, e.g., ventilation, dehumidification or depressurisation.

Table 4.4 categorises potential condensation control measures for the building envelope.

Table 4.4 Condensation control strategies for the building envelope after Lstiburek and Carmody [40] and Ten Wolde and Rose [46]

Strategy	Aim	Measure
Control of moisture access	Eliminate air leakage	Air barrier
	Restrict vapour diffusion	Vapour retarder
Control of moisture accumulation	Raise temperature of condensing surface	Insulation outside of condensing surface
	Allow harmless accumulation	High moisture capacity at condensing surface
Removal of moisture	Promote drying	Vapour permeable layers
		Capillary active layers
		Cavity ventilation
	Remove condensation	Drainage
Reduction of moisture load	Limit construction moisture	Initially dry materials

Table 4.5 Reduction of moisture load by building design and operation after Lstiburek and Carmody [40] and Ten Wolde and Rose [46]		
Aim	**Design**	**Operation**
Limit vapour in interior air	Natural ventilation system	Mechanical ventilation Dehumidification
Control air pressure differentials	Airtight floor separations (limit thermal stack height)	Depressurisation

Table 4.5 lists measures to restrict the moisture load by proper building design and operation. The individual measures may be combined to create an effective condensation control system. This way the integral building envelope and even the building may be regarded as a protective system for moisture control.

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5 Use of Polymers in Civil Engineering Applications

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5.1 Geotechnical Engineering Applications

Yildiz Wasti

5.1.1 General

The utilisation of polymers in 'Geotechnical Engineering' (a sub-discipline within civil engineering which covers broadly all forms of soil or the earth's crust – related problems) constitutes a major range of applications for these materials. The term 'geosynthetic' has been coined to describe the 'synthetic' polymers, almost exclusively thermoplastics, used for 'geotechnics' problems including environmental geotechnology.

The American Society for Testing and Materials (ASTM) has defined geosynthetic in *D4439-02 Terminology* [1] as follows: 'a planar product manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering related material as an integral part of a man-made project, structure, or system.' They are generally used in place of, or to enhance the function of, natural soil materials. Common geosynthetic polymers are polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), polyethylene terephthalate (PET), polyamide (PA), polystyrene (PS) and chloro-sulfonated polyethylene (CSPE). In all cases additives are used as colorants, ultraviolet (UV) light adsorbers, plasticisers, antioxidants, biocides, flame retardants, thermal stabilisers, lubricants, forming agents or antistatic agents [2]. Carbon black and UV stabilisers are the most common additives for protection from weathering.

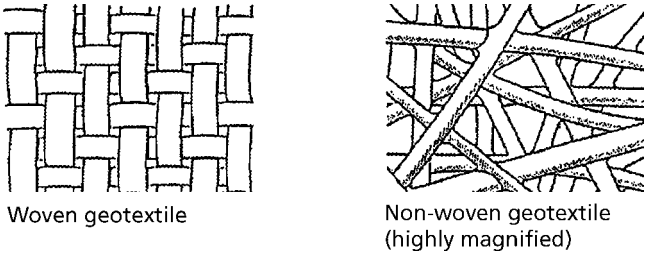
The main types of geosynthetics are geotextiles, geomembranes, geogrids, geonets, geocomposites and geosynthetic clay liners. Estimations of the market activity of these products in North America between 1970 and 1992 given by Koerner [2] show a continued growth, which is probably still very strong. The amount of geosynthetics used in 1992 in North America alone is estimated to be about 485 million m^2, with geotextiles having the greatest utilisation (~ 325 million m^2), followed by geomembranes, geocomposites, geonets, geogrids and the more recently developed geosynthetic clay liners, in decreasing order. On the basis of cost however, geomembranes have the greatest market share. Globally 1,400 million m^2 of geotextiles, which comprise 75% of all geosynthetics, are used each year [3]. As of 1998 there were more than 600 different products available in North America alone [4].

Geotextiles are permeable geosynthetics, which form the oldest and largest group of geosynthetics. They are mainly of two types: woven and nonwoven as illustrated in **Figure 5.1a**. The woven geotextiles are made on conventional textile weaving machinery using monofilament, multifilament, or fibrillated yarns, or slit films and tapes. There are subdivisions of nonwoven geotextiles, based upon the way the fibres (or filaments) are bonded together: mechanically bonded or needle-punched in which the fibres are entangled by specially designed needles, heat bonded, in which the fibres are welded together by heat and/or pressure at fibre crossover points, and chemical or resin bonded in which fibrous web is either sprayed or impregnated with an acrylic resin. Woven geotextiles generally have relatively high strength and stiffness (which makes it possible to use them in soil reinforcement applications as well) and, relatively poor filtration/drainage characteristics. Nonwoven geotextiles have low to medium strength with high elongation at failure, and good filtration/drainage characteristics. Fabric, engineering fabric or filter fabric is synonymous with the newer term 'geotextile'. The main polymer material used in the manufacture of geotextiles is polypropylene but polyester is also used [2].

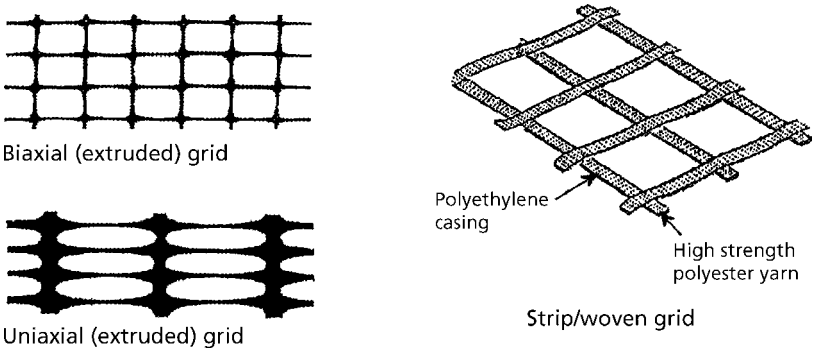
Geomembranes are very low-permeability geosynthetics used as fluid or vapour barriers. The most widely used geomembranes are thin, flexible sheets mainly of PVC, CSPE, high-density polyethylene (HDPE) and very-low-density polyethylene (VLDPE). Geotextiles impregnated with asphalt or sprayed with polymeric mixes or geotextile – bitumen geocomposites are also used as geomembranes. Polymeric sheet geomembranes are manufactured by extrusion, calendering and spread coating methods. All polyethylene geomembranes are manufactured by the extrusion method and processes called 'texturing' are used to obtain a roughened HDPE and VLDPE surface. Details of various methods used to produce geomembranes, geomembrane seaming methods and seam tests are given by Koerner [2]. Environmental regulations being enacted all over the world especially for the hazardous waste disposal call for extensive mandatory utilisation of geomembranes.

Geogrids are grid like materials with apertures of sufficient size to interlock with the surrounding soil and are used for reinforcement. Extruded grids are manufactured by first punching a regular pattern of holes into the polymer sheets (polyethylene for uniaxial and polypropylene for biaxial grids) and then stretching the sheet uniaxially or biaxially. A more flexible type of geogrid which may be called a 'woven' or 'strip geogrid' is manufactured from two sets of high-tenacity polyester yarns which intersect at 90° and are joined at the crossover points by a knitting or heat welding process, and then coated with a polymer usually polyethylene, polyvinyl chloride or bitumen (**Figure 5.1b**).

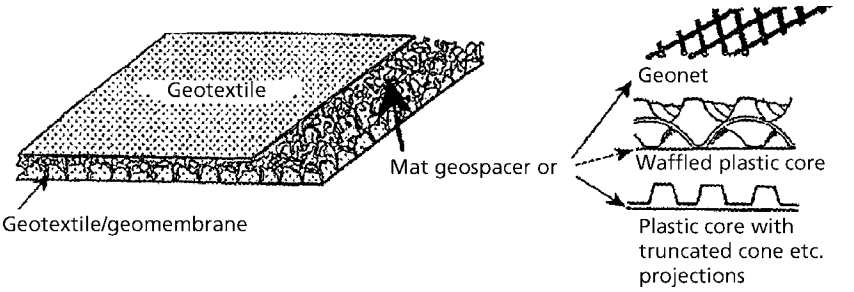
Geonets consist of two sets of parallel, roughly round polymer strands usually intersecting at between 60 to 90° and forming a mesh-like appearance. Although they can be used as comparatively low strength soil reinforcement, their main utilisation is as the core or spacer material in composite drainage products for conveyance of liquids or gases. Geonets are usually manufactured from PE, by a continuous extrusion process [2].



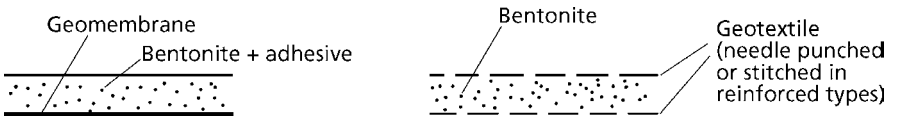
(a) Geotextiles



(b) Geogrids



(c) Geocomposite sheet drain



(d) Geosynthetic clay liners

Figure 5.1 Examples of various geosynthetics

Geocomposites consist of various combinations of geotextiles, geogrids, geonets, geomembranes, and/or other materials. Most geocomposites have been developed for drainage applications (**Figure 5.1c**).

Geosynthetic clay liners are low permeability composites typically consisting of a thin layer of dry bentonite clay, supported by geotextiles and/or geomembranes which are held together by needling, stitching, or adhesives (**Figure 5.1d**).

More information on geosynthetic types, manufacturing processes, properties and construction techniques can be found in [2, 5 and 6].

Geosynthetics have six basic functions:

1. *Separation:* Prevention of the inter-mixing of particles from dissimilar soil layers, commonly a fine-grained soil and a granular drainage soil.

2. *Filtration:* Use of geotextiles as filters to permit the flow of water across the geotextile without significant migration of soil fines into drainage aggregate or pipes.

3. *Drainage or fluid transmission*: Allowing water (or vapour) to be transmitted in the plane of a thick nonwoven needle-punched geotextile or a drainage geocomposite.

4. *Reinforcement:* Imparting tensile strength to the soil.

5. *Sealing or fluid barrier*: Impeding the flow of a liquid (or gas) using geomembranes or geotextiles which are field sprayed or impregnated with bitumen or polymeric mixes.

6. *Protection:* Protection of geomembrane against puncture by means of a cushion of nonwoven geotextile.

Although in many applications it is possible to identify one dominant or primary function, geosynthetics usually perform one or more essential secondary functions.

5.1.2 Geosynthetic Properties and Testing

Geosynthetics have a wide range of physical and mechanical properties because of the enormous number of products available and the new ones being added regularly. Nevertheless, the following list covers the range of important properties required to evaluate the suitability of geosynthetics for most geotechnical applications:

1. *General Properties* (commonly given in sales brochures)

   (a) Geosynthetic type and manufacturing process

(b) Polymer type/density

(c) Thickness

(d) Mass per unit area

(e) Roll length, width and weight

2. *Mechanical Properties*

(a) Short-term tensile strength

(b) Long-term tensile strength (creep behaviour)

(c) Resistance against tear, puncture and impact (for installation survivability)

(d) Interface shear strength/friction between soil – geosynthetic or between geosynthetics

(e) Resistance against abrasion

3. *Hydraulic Properties*

(a) Apparent (characteristic) opening size of geotextiles

(b) Percentage open area for woven geotextiles

(c) Water permeability characteristics for flow, perpendicular to the plane of geotextile: permeability/permittivity

(d) Long-term flow capability/clogging resistance of geotextiles

(e) In-plane flow capacity of thick geotextiles and drainage geocomposites: transmissivity

5. *Durability/Degradation Properties*

(a) Resistance to weathering:
Ultraviolet light
Temperature
Oxygen

(b) Resistance to chemical degradation:
Oxidation
Hydrolysis

(c) Resistance to biological degradation:
Micro-organisms
Macro-organisms

5.1.3 Use of Geosynthetics in Roadways, Pavements, Runways and Railways

For geosynthetic design purposes, roads may be broadly classified into two categories: unpaved and paved roads. Unpaved roads are those in which the pavement material is unbound stone aggregate placed on the subgrade which is the base layer of a road or the natural ground under the pavement. They are usually of a temporary nature such as haul roads used by large trucks for transporting mined or other material, access roads, detours and construction platforms. Unpaved road performance requirements allow for some rutting to occur. In the case of weak subgrades, such as soft clays, water bearing silts, intermixing of the aggregate and the subgrade soil with the associated loss in aggregate thickness and structural support eventually makes the road impassable or in need of constant maintenance. Paved roads are defined as those where the upper part of the pavement structure is bound – usually by bitumen or concrete - overlying the granular base and sub-base layers. Pavement failure is expressed in terms of decreased serviceability caused by the development of cracks and ruts.

Geosynthetics have been used in new road construction in various ways to minimise the previously mentioned problems as well as in the maintenance of existing paved roads (overlays applied to strengthen existing pavements). In this category of application the two principal roles for geosynthetics are *separation/filtration*, and *reinforcement*. The use of geosynthetics to perform these functions in unpaved and paved roads is discussed in Section 5.1.3.1 and 5.1.3.2.

5.1.3.1 Use of Geosynthetics in Unpaved Roads

Incorporating a geotextile in the road construction as a separator at the interface between soft, fine-grained subgrade soil and aggregate (**Figure 5.2**) was the first application of geosynthetics in roads. In this application the geotextile separator must perform a filtration function as well, preventing particles smaller than about 0.06 mm in size called soil fines from migrating into the aggregate and avoiding build-up of excess pore water pressures. In addition, the geotextile may provide reinforcement through lateral restraint of the subgrade soil and additional support to the wheel loads due to the membrane action of the geotextile in tension. Geogrid reinforcements applied between the soil and the granular layer can lock the granular particles together and prevent repeated strains on the soil that can cause slurry to form and pumping of the slurry up into the granular layer, but ideally a geotextile must be used together with the geogrid.

Geogrid reinforcement placed at approximately mid-depth of the granular layer (unless the layer is very thick), is also suggested for the control of rutting through restriction of permanent strain development in the granular layer [7]. Stiff extruded geogrids are suitable for this application. Possible locations for geosynthetics in unpaved roads are given in **Figure 5.3**.

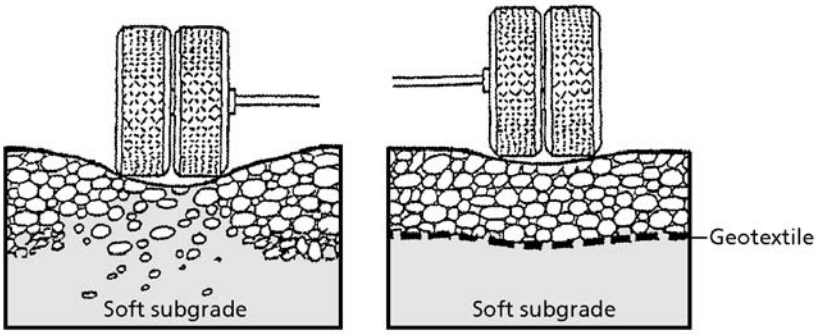
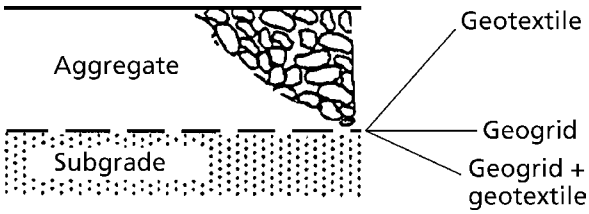
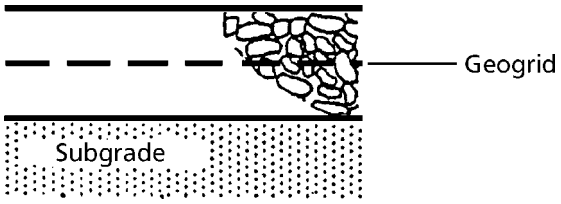


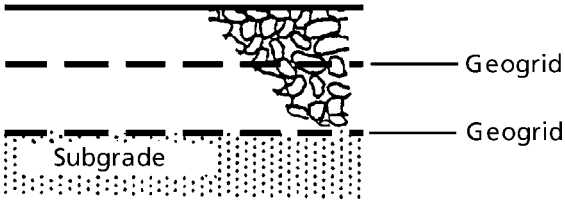
Figure 5.2 Mechanism for geotextile separation in unpaved road



(a) Weak subgrade, good aggregate



(b) Stiff subgrade, poor aggregate



(c) Weak subgrade, poor aggregate

Figure 5.3 Locations for geosynthetics in unpaved roads

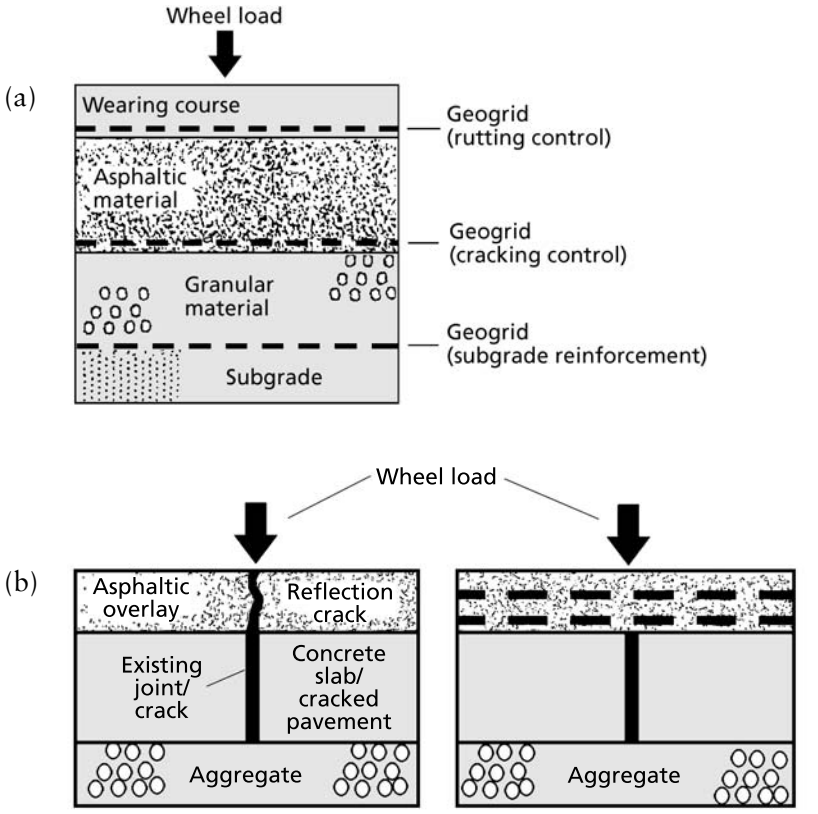


Figure 5.4 Locations for geogrid reinforcement and function in (a) asphalt pavement and (b) asphalt overlays

5.1.3.2 Use of Geosynthetics in Paved Roads/Pavements

In a paved road, a geotextile can be placed at the interface between the granular subbase and the soft subgrade soil to function in the same way as in an unpaved road in preventing loss of granular material into the soft soil since the granular layer supports the construction plant during the construction stage (**Figure 5.2**). A geotextile separator can be used simply as a construction expedient for wet sites as well.

For asphalt pavement reinforcement, stiff extruded geogrids are the best option and the best locations are [7]:

(i) Near the underside of the asphalt layer of a pavement where the tensile stress and strain is a maximum, to inhibit fatigue cracking (**Figure 5.4a**).

(ii) Near the upper surface of the asphalt layer to reduce rutting (**Figure 5.4a**).

(iii) At the interface of the existing pavement and asphalt overlay to reduce the development of reflection cracking.

Alternatively, in overlays, geotextiles placed on the existing road surface which has been cleaned and sprayed with an asphaltic sealant before the hot mix overlay is installed, help to control subsequent reflection cracking and also provide a waterproofing layer for controlling surface water infiltration. Use of a geosynthetic in overlays for reflection cracking control has been the most popular application in asphalt paving. A geogrid located at mid-depth of the overlay reduces rutting in the overlay (**Figure 5.4b**).

Use of geosynthetics for taxiways, runways and car parks follows the same principles as for paved roads.

5.1.3.3 Use of Geosynthetics in Railways

Railways tracks are supported by granular material called 'ballast'. The application of geosynthetics in railways is therefore somewhat similar to unpaved roads and can be considered basically in two categories:

(i) A geotextile separator/filter at the interface between the ballast and soft clayey subgrade.

Slurries produced from cohesive subgrades beneath railway ballast can be pumped into the ballast under the action of the dynamic train loading to give the condition known as 'erosion pumping'. The load support capability of the ballast is reduced as a result of the contamination of the ballast, eventually leading to unacceptable movements of the rails. The problem is addressed by the provision of a sand blanket (filter) on the subgrade. Geotextile filters can be incorporated in the design to replace the sand blanket or, even better, with a thin layer of sand blanket. There appears to be some agreement between North American and European practice on the use of generally thick, nonwoven needle-punched geotextiles for subgrade separation application in railways [6].

(ii) Ballast strengthening using a stiff geogrid within the ballast to reduce the permanent deformation of the ballast due to the repetitive vibratory train loads.

5.1.4 Use of Geosynthetics in Drainage and Erosion Control Systems

(a) Use of geotextiles to perform a 'filtration' function (in situations where the flow is perpendicular to the plane of the geotextile) as a replacement for or in conjunction with conventional granular filters. This is one of the major areas of geotextile use.

Examples in drainage systems are: *Geotextile filters* around drainage aggregate or perforated/slotted pipes in various types of drains for land drainage, highway drainage, structural drainage for retaining walls or buildings (**Figure 5.5a**), *earth dam drainage* (chimney and toe drains).

Examples of the use of a geotextile in erosion control measures are: beneath large stones employed in revetments called riprap, armour stone, concrete block, gabion mattress type revetments (which are wire-mesh boxes filled with stones) for rainfall/runoff, coastal/stream bank erosion protection (**Figure 5.5b**) and in scour protection for bridge piers and abutments. Geosynthetic erosion control blankets or mats manufactured from both natural (straw or coconut fibres) and polymer meshes/webbings are also used, to enhance the establishment of a vegetative cover on slopes prone to erosion by rainfall and runoff.

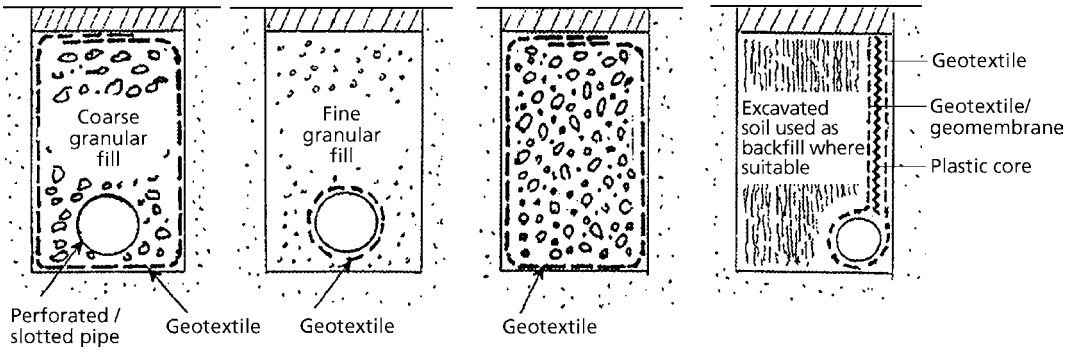
(b) *Applications where the in-plane drainage ability of a thick geotextile or mostly a geocomposite drain is utilised.* Composite drains have a water conducting spacer core of extruded and fluted plastic sheets, geonets, waffled plastic sheets, meshes and mats with a geotextile filter on either one or both sides (**Figure 5.1c, Figure 5.5a**). They may be prefabricated or fabricated on site. They have been used as highway edge drains, highway shoulder drains, structural drains and band/strip drains as a substitute for vertical sand drains to induce rapid consolidation of soft clays (**Figure 5.5c**).

5.1.5 Use of Geosynthetics in Soil Reinforcement Applications

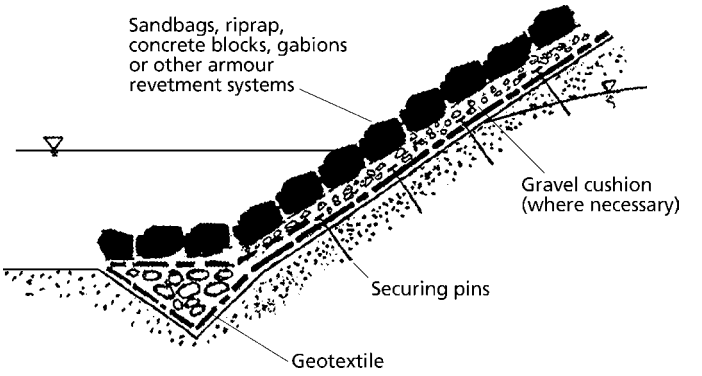
Geosynthetics with high tensile strength and stiffness such as geogrids, woven tapes/strips are used in reinforcement applications. Examples are: reinforced soil walls, reinforced steep slopes, slope repair by reinforced soil, basal reinforcement at the base of embankments on soft ground or embankments over piled foundations, as illustrated in **Figure 5.6**.

5.1.6 Use of Geosynthetics in Waste Disposal Facilities

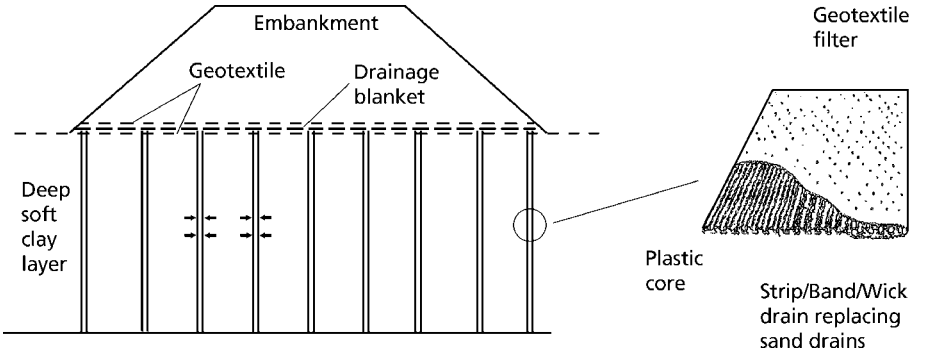
Environmental regulations dictate that landfills and surface impoundments for the disposal of hazardous and non-hazardous waste have liners (base, side-slope, and cover liners) and a leachate (contaminated water that emanates from a disposal site) collection and removal system in order to protect air, water, and land resources. Base and side-slopes of containments are lined with compacted clay or geomembrane (commonly HDPE) or both. Cover liners generally incorporate a foundation material overlain by a clay and/or geomembrane (commonly VLDPE which is more flexible than HDPE) liner. Geosynthetic clay liners may be used in place of clay. The leachate collection and removal system is



(a) Use of geotextile filter/drainage geocomposite in trench drains

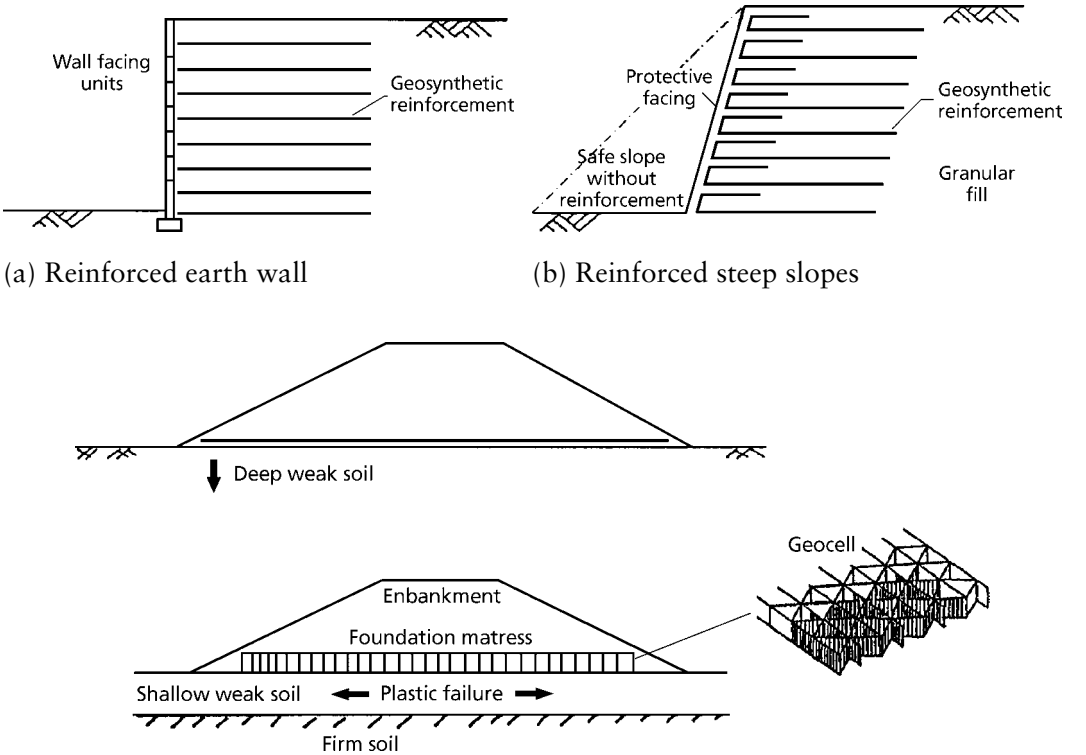


(b) Slope / Streambank / Coastline erosion control



(c) Vertical drains to accelerate consolidation

Figure 5.5 Examples of filtration, erosion control and drainage applications



(a) Reinforced earth wall

(b) Reinforced steep slopes

(c) Embankment on soft foundations

(d) Piled embankment

Figure 5.6 Examples of reinforcement applications

essentially a granular drainage layer and perforated leachate collection pipes (commonly of HDPE) at the base of the waste containment facility. A drainage layer may be placed on the cover liner as well to reduce infiltrating water through the liner.

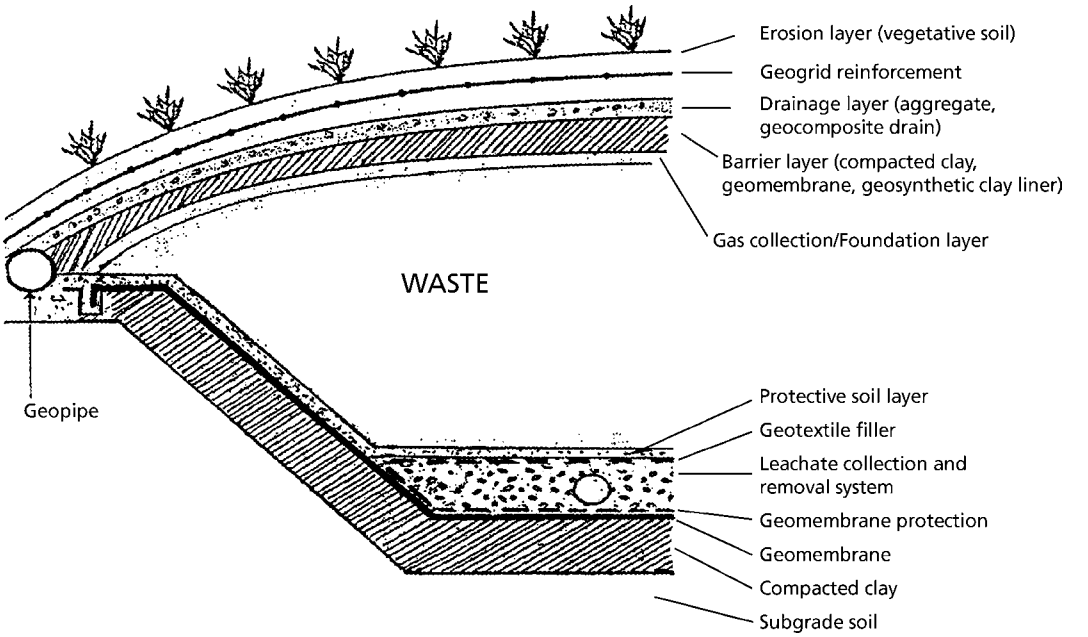


Figure 5.7 Geosynthetics in landfill containment

Other geosynthetics are also used in waste containment systems: geotextiles as filters and separators protecting drainage layers, geonets as drains in place of granular material, geocomposite drains for removal of surface water and geogrids for slope and subsidence reinforcement (**Figure 5.7**).

5.1.7 Miscellaneous Applications of Geosynthetics

Other noteworthy examples of geosynthetic applications are:

- Use of geotextiles in silt fences, which consist of geotextiles placed vertically on posts to prevent eroded material from being transported away from the construction site by runoff water.

- Use of geomembranes in canal, tank and tunnel linings, as impervious cores or upstream blankets in earth dams, as waterproofing rehabilitation in the upstream face of old concrete or masonry dams and in vertical cut-off walls in earth dams, around waste sites and in encapsulating swelling soils.

- Use of 'geofoams', with polystyrene foam having the strongest market share, for thermal insulation, vibration damping, as lightweight fill material and in the form of a compressible inclusion, i.e., a foam layer placed in contact between a non-yielding structural element such as a foundation or wall and the ground.
- Use of 'geocells' (a row of geogrid cells typically one metre high, filled with sand or gravel) as foundation mattresses below embankments (**Figure 5.6c**).
- Use of buried plastic pipes also called 'geopipes', for pipeline transmission of water, gas, oil and in drainage systems for buildings, retaining walls, tunnels, highways, railways, slopes, landfills, etc. PVC, HDPE, PP, polybutylene (PB), acrylonitrile butadiene styrene (ABS) and cellulose acetate butyrate (CAB) are the polymer resins in current use in the fabrication of these pipes [2].

5.2 Polymers in Concrete

Mustafa Tokyay

Concretes with polymers are generally classified into three categories as polymer concrete (PC), polymer Portland cement concrete (PPCC), which is also known as latex-modified concrete (LMC) and polymer-impregnated concrete (PIC) according to their process technologies.

Polymer concrete is a composite material formed by polymerising a monomer and aggregate mixture. There is no other cementitious material present in it. PPCC (or LMC) is a Portland cement concrete produced usually by replacing a specified portion of the mixing water with a latex (polymer emulsion). It can also be produced by adding a monomer to fresh concrete with subsequent *in situ* curing and polymerisation. PIC is a hardened Portland cement concrete with impregnated monomer which is polymerised *in situ*.

Concretes containing polymers are causing much interest as high performance or multi-functional materials in the construction industry. PPCC was developed in late 1920s, polymer concrete in 1950s and PIC in late 1960s. Currently, the first two types are being used as popular construction materials whereas PIC has not yet been used much due to its relatively higher processing cost although it performs very well.

A general classification of concrete-polymer composites is given in **Figure 5.8** [8].

5.2.1 Polymer Concrete

Binders used for polymer concrete include epoxy resins (EP), unsaturated polymer resin (UP), vinyl ester resin (VE), methyl metacrylate (MMA) and furan resins [9-11].

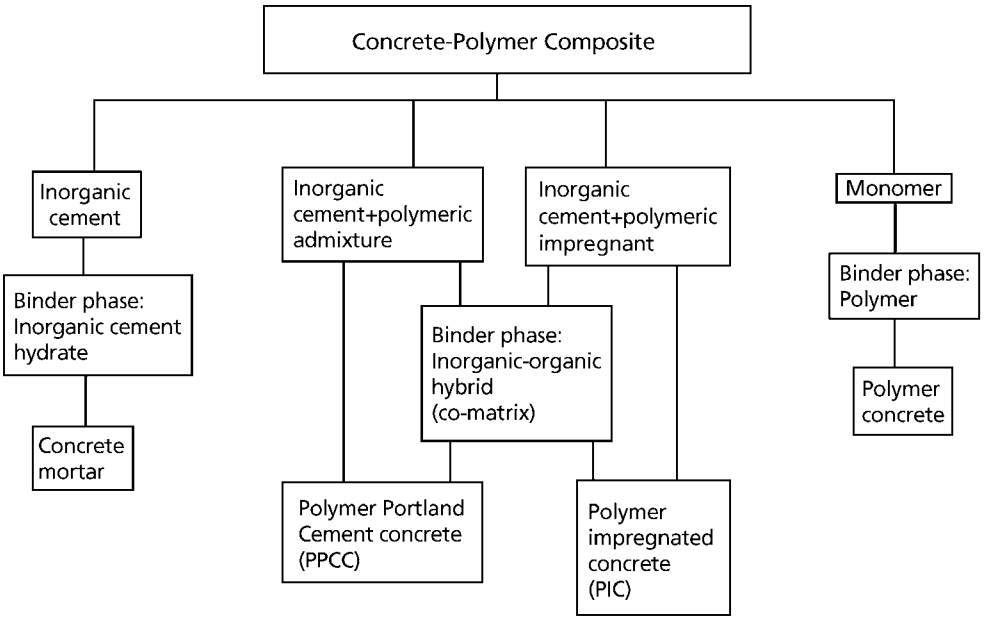


Figure 5.8 Classification of concrete-polymer composites [8]

The properties of polymer concrete depend on the characteristics of the polymer and the aggregate used and the formulation [12, 13]. Broadly speaking, the unique properties of polymer concrete are [13]:

(i) High strength (tensile, flexural and compressive),
(ii) good adhesion to most surfaces,
(iii) long-term freeze-thaw durability,
(iv) low permeability, and,
(v) high chemical resistance.

5.2.1.1 Production

Polymer concrete production uses equipment and methods that are being used for producing Portland cement concrete. In the design of polymer concrete mixes, the main objective is to obtain a suitable particle size distribution of the aggregate so that a good workability will be attained with a minimum amount of monomer or resin [9]. Aggregates should be dried to at least 3% moisture [11] but moisture contents less than 1% are preferred as moisture reduces the bond between the binder and the aggregate [14].

There are numerous formulations of polymer concrete as each one is designed for a specific application. Epoxy resins with proper curing agents are the most commonly used polymer concrete binders. The aggregate:resin ratio may range between 1:1 and 15:1 by weight, depending on the aggregate gradation.

The initiators for monomers are benzoyl, lauroyl or methyl ethyl ketone peroxides. The promoters for monomers are tertiary amines like dimethyl aniline or dimethyl-*p*-toluidine. Epoxy compounds are usually formulated in two parts as epoxy resin and the hardener [11].

5.2.1.2 Uses

Applications of polymer mortars and polymer concretes include patching of Portland cement concrete, floor and pavement overlays, anti-corrosive linings, precast products, vaults, panels [8, 11]. These indicate that there is no single polymer concrete that performs all of these tasks. Application and performance of polymer concrete depend on the binder used and the aggregate. Copolymerisation techniques allow the production of a wide range of binders with varying properties [11].

Repair Materials: When polymer concrete is to be used for repair or patching purposes, it is necessary to obtain a strong, sound, dry and clean surface for treatment. Otherwise, a poor bond would occur between the surface and the repair material. All the deteriorated and unsound material should be removed with special care taken for not damaging the surrounding areas and not impairing the bond of remaining sound concrete with the reinforcement.

Polymer concrete can be placed by either premix, dry pack or prepack methods. The premix method is similar to the conventional Portland cement concrete mixing and placing. The binder, fine aggregate and coarse aggregate are added to the mixer in that order and mixing is continued until all aggregate particles are thoroughly wetted. Then the material is placed where it is required and consolidated. It is usually recommended that the surface to be treated is primed with the binder before placement.

The aggregate with specified grading is placed in the area to be repaired and compacted by tamping in the dry pack method. Then the monomer mixture is applied to the aggregate, placed by means of a dispenser until all the aggregate is wetted. Usually, monomers of viscosities less than 0.1 Pa-s are necessary for this method.

In the prepack method, monomer or resin is fed into the mixer, after adding the fine aggregate, the coarse aggregate is introduced and the entire blend is mixed for a specified time. The composite is then placed where required and consolidated.

Overlays: polymer concrete overlays are used to get a durable, almost impervious and wear-resistant surfaces on Portland cement concretes. Suitable surface texture may be obtained for appropriate skid resistance and hydroplaning characteristics. The surfaces on which overlay will be applied must be prepared to ensure good adhesion. The surface must be strong, sound, dry and clean. The monomer and aggregate systems used for polymer concrete overlays are similar to those of polymer concrete repairing materials.

There are four different methods of applying polymer concrete overlays:

(i) thin sand-filled resin overlay,
(ii) polymer seal coat overlay,
(iii) premixed polymer concrete overlay, and,
(iv) prepacked polymer concrete overlay.

For thin sand-filled overlays, a thin layer of initiated and promoted resin is applied to the concrete surface. Before the resin starts to gel, aggregate is spread over. Upon completion of curing, the excess aggregate is swept off. This cycle is repeated three or four times until a nonpermeable and skid resistant overlay is obtained.

In polymer seal coat application, a 6-7 mm layer of dry sand is placed upon the concrete surface then a strong sandstone is put on the sand and hand rolled to set the aggregate. First, a low viscosity monomer mixture is applied. Then, the viscosity is increased by polymer addition and spread over the aggregate surface. Usually, surfaces are covered to minimise monomer evaporation.

In premixed polymer concrete overlays, the aggregate and the monomer or resin system are mixed together in a concrete mixer and then spread over the surface and compacted. Sometimes, additional aggregate may be applied on the surface to increase skid resistance. Most of the time, a primer coat of initiated and promoted resin is applied on the concrete surface on which the overlay is to be placed.

Precast Elements: There are numerous applications of precast polymer concrete such as panels, pipes, drainage channels, tiles, bricks, linings, manhole structures, stair treads, electric insulators, etc. [11, 15].

The method of producing precast polymer concrete is similar to that of precast Portland cement concrete. The extremely short hardening period of polymer concrete is an obvious advantage over Portland cement concrete. Form removal may be as short as 40 seconds, depending on the type of monomer used [11]. The formwork, vibrators and mixers used in producing polymer concrete precast elements are no different to those used for Portland cement concrete precast elements. However, it should be noted that the formwork should be durable, smooth surfaced and must be able to withstand the heat developed during the exothermic polymerisation process.

Form vibration is preferable to internal vibration in polymer concretes and low viscosity monomers require low-frequency high-amplitude vibration whereas high viscosity monomers are better consolidated by high-frequency low-amplitude vibration.

5.2.2 Polymer Portland Cement Concrete

PPCC mixtures are Portland cement concrete mixtures to which polymer latexes have been added during the mixing process. Hardening of the polymer occurs simultaneously with the curing of concrete thus forming a continuous polymer network throughout the concrete [11, 16].

Although many different polymers were investigated for use in PPCC, latexes are the most widely used binders. The latexes that are in general use are styrene-butadiene rubber (SBR) and chloroprene rubber (CR) which are elastomeric; polyacrylic ester (PAE), ethlene-vinyl acetate (EVA) and poly(styrene-acrylic ester) (SAE) which are thermoplastic. Besides latexes, epoxy resins, which are thermosetting, are also used in PPCC [11, 17].

The mixing and placing operations of PPCC are similar to those of Portland cement concrete. Curing, on the other hand, is different. Portland cement concrete requires comparatively long curing periods under 100% relative humidity whereas PPCC needs one day of moist curing after which polymer membranes surrounding the cement paste form and retain the water inside for continued cement hydration [17].

After one day of moist curing and at least three days of air curing at 7-30 °C, the PPCC can be put safely into service [11]. Rewetting may result in re-emulsifying or redispersion of the latex with consequent strength reduction.

The most important feature of PPCC is its excellent bonding characteristics. However, this may sometimes cause problems of form removal unless suitable release agents are placed on forms [11].

5.2.2.1 Uses

PPCC applications include deck coverings, floors, pavements, precast units, anti-corrosive linings, adhesives, patching or repairing Portland cement concretes [11, 17].

Deck Coverings: Deterioration of reinforced concrete by the ingress of moisture, oxygen and chlorides resulting in the corrosion of reinforcement and subsequent spalling of concrete may cause serious problems especially in bridge decks [11, 18].

The dispersed polymer phase throughout the concrete causes considerable reduction in porosity and microcracks in the Portland cement matrix as well as serving as an additional binding material [11, 19]. Thus, PPCC is a more durable and weather resistant material for deck coverings and parking lot overlays.

Floors and Pavements: The chemical resistance and overall improvement in the physical and mechanical properties of PPCC makes it a suitable material especially for industrial floor applications where chemical spills and heavy traffic are the typical problems encountered.

Precast Units: PPCC is suitable for precast operations due to its good workability and heat-curing characteristics. Since most polymers also have a water reducing effect, it is possible to obtain PPCC with low water:cement ratios. Although high temperature curing is beneficial, care should be taken to prevent the direct contact of steam with the PPCC units. Otherwise, moisture may cause strength reduction [19].

Patching and Repair: Very high bond strength of PPCC makes it a suitable material for patching and repair of portland cement concrete. The deteriorated or unsound concrete must be removed properly before PPCC application.

5.2.2.2 PPCC Mix Proportions

The mix proportions of any PPCC depend on the intended use and the type of polymer. In general, the solid content of the polymer used ranges between 10-20% (by weight of cement used). The cement content should be sufficiently high (usually, more than 400 kg/m^3). Total aggregate constitutes about 70% (by weight) of the whole mix and the coarse aggregate-to-fine aggregate ratio depends on the surface finish required. Typical water:cement ratios of PPCC range between 0.25 and 0.40. It must be remembered that, emulsions contain water and that amount should also be included in the total mixing water when calculating the mix proportions [11]. Suggested guidelines for PPCC mix proportioning may be found in [11].

5.2.2.3 Preparation, Mixing, Placing and Curing Procedures

Before placing the PPCC as an overlay or patch, the concrete surfaces to be covered must be prepared appropriately. The surface is to be cleaned within 24 hours of placement. All unsound concrete and foreign materials including rust and oil must be removed in order to ensure a strong bond between the existing surface and the PPCC overlay. For the cases that necessitate complete removal of the existing concrete, forms should be provided for a proper placement of PPCC.

The cleaned surfaces should be wetted thoroughly one hour before placement. However, any standing water on the surface must be removed by compressed air prior to PPCC application.

The corroded reinforcements should be blast-cleaned. The reinforcing bars that have lost more than one-quarter of their original diameter should be replaced by new ones. If the bond between the existing concrete and the reinforcement is destroyed or more than half of the reinforcing steel diameter is exposed, the concrete around the reinforcement should be removed to leave at least 19 mm clearance so that PPCC will bond to the entire reinforcing steel. Care should be taken to prevent damage to the exposed reinforcement [11].

For overlays, PPCC is mixed on site and brushed onto the exposed surfaces. The PPCC should be covered with wet burlap (coarse jute fabric) and a layer of polyethylene film on top of it. After 24 hours of wet curing, the burlap and polyethylene are removed and PPCC is let to dry out for at least 72 hours. Then the traffic may be permitted on the surface.

PPCC is usually placed at temperatures above 7 °C. At lower temperatures curing periods should be extended [11].

5.2.3 Polymer Impregnated Concrete

PIC are formed by drying the Portland cement concrete, removing the air in the voids, adding by diffusion a low viscosity (<0.1 Pa-s) monomer by atmospheric or pressure soaking and polymerising the monomer [11]. Depending on the degree to which the void volume of concrete is filled with monomer, PIC are divided into two groups: partially impregnated and fully impregnated. Full impregnation implies that approximately 85% of the void space is filled. If the ratio of the filled voids to the total available void content is less than that then partial impregnation is attained. Sometimes, partially impregnated concrete is also called surface impregnated concrete because it is impregnated to a limited depth beneath the surface [11].

After impregnation the monomer in the system is polymerised by either thermal-catalytic or promoted-catalytic or ionising radiation methods. The catalytic methods are more commonly used than the latter [11].

The thermal-catalytic method involves the use of chemical initiators and heat. Commonly used initiators include benzoyl peroxide (CFRP), azobis-isobutyronitrile, α-*tert*-butyl-azoisobutyronitrile, *tert*-butylperbenzoate, and methylethylketone peroxide (MEKP) [11].

In order to allow polymerisation at low ambient temperatures, the promoted-catalytic method may be used. This is achieved by promoters which are reducing agent compounds

added to the monomer for the decomposition of the peroxide initiators to produce the free radicals needed for polymerisation. The promoters that have been successfully used include methyl anilines, dimethyl-*p*-toluidine, cobalt naphthalene and mercaptans [11].

Another way of achieving polymerisation at low temperatures is by using ionising radiation from gamma rays emitted by cobalt-60. The radiation energy absorbed by the monomer results in the production of free radicals. The radiation method does not require initiators or promoters. On the other hand, the cost of radiation source is high and polymerisation rate may be low [11].

The selection of a monomer for PIC depends on its impregnation and polymerisation characteristics. Vinyl monomers such as acrylonitrile, methyl methacrylate, styrene and vinyl acetate containing an initiator are the most commonly used materials for PIC production.

Various additives and modifiers are frequently used in PIC to produce desired changes in the properties. Plasticisers like dibutylphtalate (DBP) increase the flexibility in brittle polymers, whereas crosslinking agents like trimethylolpropane trimethacrylate (TMPTMA) increase the rigidity and the softening temperature of the polymer. Initiators act as catalysts and promoters accelerate the polymerisation. Silane coupling agents can be used to improve the strength of PIC by forming chemical bonds between the polymer and the surrounding inorganic matrix.

5.2.3.1 Partially Impregnated PIC

Partially impregnated concrete, which is also called surface impregnated concrete, is usually accomplished by a simple soaking technique. The main objective of partial impregnation is to obtain an in-depth protective zone of reduced permeability on the surface of the concrete. Thus, improvement in durability rather than strength is aimed for by use of partial impregnation.

The partial impregnation process consists of the following steps:

(1) surface preparation,
(2) concrete drying,
(3) concrete cooling,
(4) monomer soaking,
(5) polymerisation, and,
(6) cleaning [11].

The application of partially impregnated PIC includes treatment of precast concrete members and existing concrete structures and restoration of deteriorated concrete structures.

5.2.3.2 Fully Impregnated PIC

Full impregnation is usually achieved by pressure. The principal reason for full impregnation is to improve the strength and other mechanical properties of concrete. Durability improvement accompanies this.

The full impregnation process consists essentially of the same steps as the partial impregnation process. Fully impregnated concrete applications are restricted to precast concrete members [9].

5.2.4 Polymer Based Admixtures for Concrete

Chemical admixtures are frequently introduced into concrete for improving one or more of its properties in the fresh or hardened state. They are usually classified according to the specific function they perform. The American Concrete Institute provides a classification in terms of air entraining admixtures, accelerating admixtures, water reducing admixtures, set controlling admixtures, and miscellaneous admixtures [20]. More detailed classifications are being used for specific groups of admixtures. For example, ASTM defines the functional properties as Type A: water reducing, Type B: retarding, Type C: accelerating, Type D: water reducing and retarding, Type E: water reducing and accelerating, Type F: high range water reducing and Type G: high range water reducing and accelerating [21].

Polymeric admixtures used in concrete are mainly for water reduction purposes. Besides this primary effect they may also have secondary effects like retardation, acceleration, or air-entrainment, depending on their formulations.

5.2.4.1 General Thoughts About Chemical Admixture-Cement Interactions

The concepts outlined next are focused on retarders, water reducing agents and air entraining agents which are the main groups of organic chemical admixtures used in concrete. Most of the organic admixtures show an affinity towards the surfaces of the cement particles or hydration products resulting in considerable adsorption. Organic molecules bearing charged groups or polar functional groups interact with particle surfaces through electrostatic forces or hydrogen bonds. Polymeric admixtures containing hydrophobic groups in addition to polar and ionic groups result in adsorption caused by the cumulative effect of all three groups [22]. The adsorbed compounds change the surface properties of the cement particles and thus their interactions with the solution phase and other cement particles [23]. Polymers and anionic surfactants result in a negative electrical

charge on the particle surface, which induces repulsion between the neighbouring cement particles and increased dispersion. When high molecular weight polymers are used, steric forces lead to additional repulsion [24, 25].

5.2.4.2 Water Reducing Admixtures

The water reducing admixtures are the materials that have the primary function of producing concrete of a specified workability at a lower water:cement ratio than that of the control concrete without admixture. The effect of water reducing admixtures on various properties of fresh and hardened concrete is illustrated in **Figure 5.9** [23, 26].

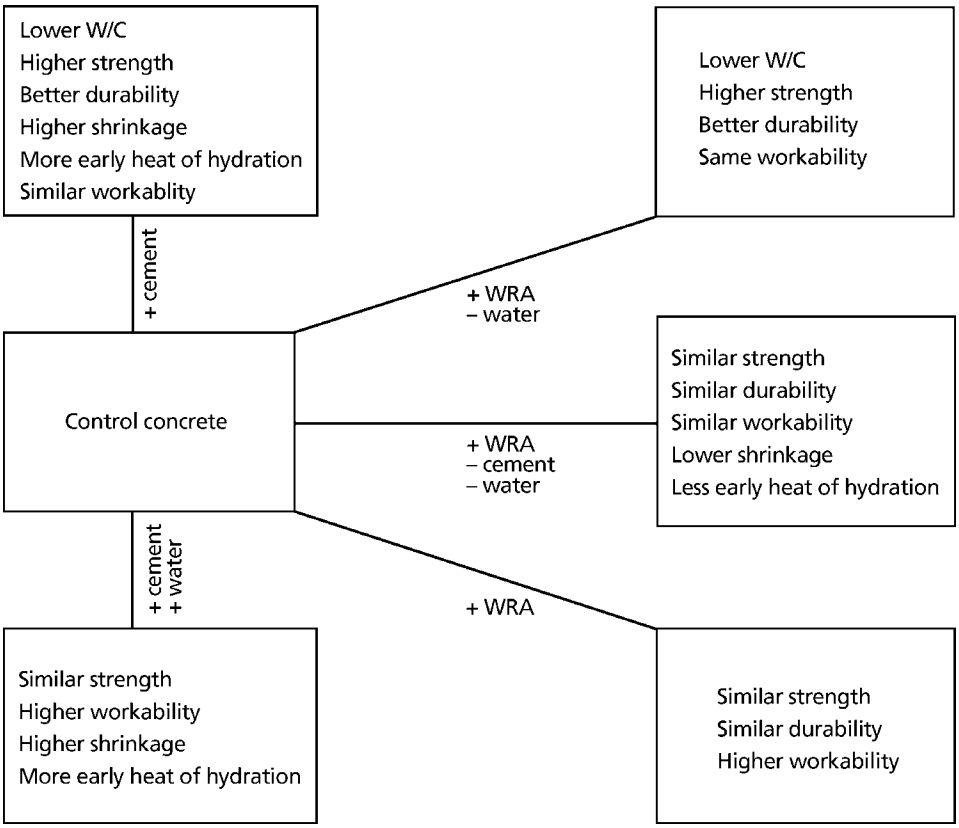


Figure 5.9 Effect of water reducing admixtures on properties of fresh and hardened concrete [23, 26].
W/C: water:cement ratio, WRA: water reducing admixture

Water reducing admixtures (WRA) are grouped into five types:

(i) normal,

(ii) accelerating,

(iii) retarding,

(iv) air-entraining, and,

(v) high-range WRA (superplasticisers) admixtures according to their secondary functions.

The accelerating WRA, besides the water reducing capability of the normal type, give higher strength earlier, which is advantageous for low temperature concreting or concrete work where higher early strength is required.

The retarding WRA, again possess the properties of the normal type but elongate the setting time of concrete resulting in increased time for transportation, handling, and placing.

The air-entraining WRA, entrain microscopic air bubbles into cement paste besides reducing the water content of the mix. Air-entrainment results in increased freeze-thaw resistance of concrete. However, air-entrainment by itself causes reduction in strength unless precautions are taken. Air-entraining WRA have the advantage of overcoming the strength reduction due to induced air bubbles by air-entrainment through reduction in water:cement ratio.

The high-range water reducing admixtures (HRWRA) which are also called superplasticisers are admixtures that reduce the mixing water requirement of a concrete with a given consistency by more than 12% [20].

There are five chemical material groups that form the basis of all water reducing admixtures. Rixom and Mailvaganam [26] categorise the basic chemicals used in **Table 5.1**.

Lignosulfonates: The lignosulfonate molecule is a substituted phenyl propane unit with hydroxyl, carboxyl, methoxy and sulfonic acid groups [26]. The polymer has a molecular weight ranging from a few hundred to 100,000. Commercial lignosulfonates used for admixtures are usually calcium- or sodium-based. The lignosulfonate by itself and the sugar present in the lignosulfonate materials result in retardation of the hydration reactions of cement. Therefore, to obtain normal or accelerating WRA, accelerating admixtures such as triethanolamine, calcium formate or calcium chloride are added [23, 26].

Many lignosulfonates, especially the less pure types, entrain a certain volume of air in concrete. This may be desirable to improve the durability of concrete against freezing and

Table 5.1 Categorisation of basic chemicals used in water reducing admixtures [25]				
Type of water reducing admixtures				
Normal	**Accelerating**	**Retarding**	**Air-entraining**	**Superplasticisers**
Pure lignosulfonate	Lignosulfonate + $CaCl_2$	High sugar lignosulfonate	Impure lignosulfonate	Pure lignosulfonate
Lignosulfonate+ air-detraining agent	Lignosulfonate + triethanolamine	Hydroxy-carboxylic acid	Lignosulfonate + surfactant	Salt of formaldehyde-naphthalene sulfonate
Hydroxy-carboxylic acid (low dosage)	Lignosulfonate + calcium formate	Hydroxylated polymer	Hydoxy-carboxylic acid + surfactant	Salt of formaldehyde-melamine sulfonate
Hydroxylated polymer (low dosage)	Hydroxy-carboxylic acid + $CaCl_2$			

thawing. However, surfactant addition to lignosulfonate is more common for this purpose. In order to reduce the entrained air content, a defoaming agent is usually added [23, 26].

Hydroxycarboxylic Acids: The hydroxycarboxylic acids have hydroxyl (OH) and carboxyl (COOH) groups attached to a carbon chain. Gluconic, citric, tartaric, mucic, malic, salicylic, heptonic, saccharic, and tannic acids can be used as retarding and retarding water reducing admixtures. For use as normal WRA they are mixed with accelerating admixtures [23]. Hydroxycarboxylic acid-based WRA are mostly used as aqueous solutions of sodium salt. However, they may occasionally be found as salts of ammonia or triethanolamine.

Hydroxylated Polymers: Hydroxylated polymers are obtained by the partial hydrolysis of polysaccharides to form polymers of low molecular weight. They have a retardation effect, by themselves. In order to be used as normal or accelerating WRA, small amounts of calcium chloride or triethanolamine should be added [23, 26].

Salts of Formaldehyde-Naphthalene Sulfonate: Although it was the first WRA referred to in the literature, it has been used in major applications only since the early 1970s. The material is obtained by oleum or sulfur trioxide sulfonation of naphthalene. The reaction of the product results in polymerisation [26]. If the material obtained is of low polymerisation, it does not result in air-entrainment. However, if they are of high molecular weight they do not result in air-entrainment.

They are commonly used to produce high-range WRA because it is possible to add them in large amounts in concrete without causing undesirable retardation or air-entrainment and resulting in considerable reduction in water:cement ratio [26].

Salts of Formaldehyde-Melamine Sulfonate: The material is prepared by normal resinification techniques through:

(i) addition of formaldehyde to melamine,

(ii) addition of sodium bisulphite to trimethylol melamine, and then,

(iii) polymerisation. The molecular weight of the resulting polymer depends on the length of the polymerisation time. A suitable high range WRA should have a molecular weight of about 30,000 [26]. It has no adverse side effects like retardation or air-entrainment.

5.2.4.3 Effects of WRA on Properties of Fresh Concrete

Workability: Workability of concrete can be defined as the ability of concrete to be placed, compacted and finished without harmful segregation. WRA are used to increase workability for a specified water:cement ratio. The increase in workability is dependent on the type and amount of the admixture used as illustrated in **Figure 5.10** [26].

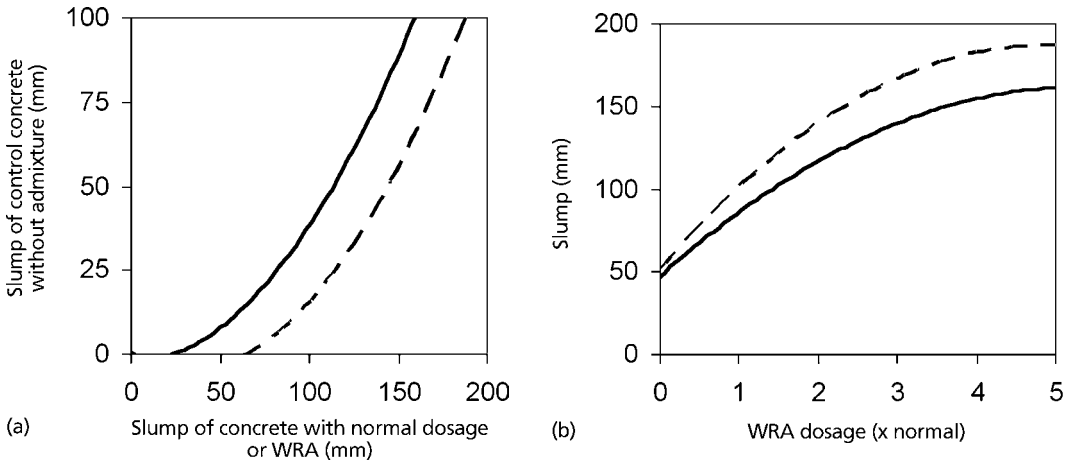


Figure 5.10 Effect of type and amount of WRA on slump of concrete: (a) Relationship between the slump of concrete with WRA and slump of control concrete; (b) Effect of the amount of WRA on slump [26]

High range WRA act in a similar manner to WRA. However, because higher dosages can be used the increase in workability is much more.

Since WRA transform stiff concrete mixes into more plastic mixes at a given water:cement ratio, they can also be used to improve the pumpability. Concrete mixes with WRA were reported to have increased pumpability even with reduced water and cement contents for a specified workability [23].

Workability Loss: Most WRA also have a retardation effect. Therefore, they reduce the workability loss, which is usually described in terms of slump (measure of concrete consistency) loss. For normal WRA, a distinction should be made between concrete mixes with a specified water:cement ratio and a specified slump. At a given water:cement ratio the slump of concrete with WRA increases considerably. Although the rate of slump loss increases upon normal WRA use, the higher slump value at the beginning causes later slump values to be still higher than those of the concrete without WRA. On the other hand, for the same initial slump, the workability loss is more rapid in normal WRA incorporated concretes than that of control concretes. A similar but more pronounced effect of loss of workability is observed in high range WRA incorporated mixes.

Bleeding: Generally speaking, WRA or HRWRA, which do not have an air-entrainment property as a side effect result in increased bleeding. Rate of bleeding increases if the admixture is used to increase workability of concrete with a specified water:cement ratio. On the other hand, if it is used to reduce the water content of the concrete mix then the amount and rate of bleeding decrease.

Air-entrainment: WRA and HRWRA generally result in approximately 1% additional air in concrete. Although the amount of air in a concrete mix depends on the type and quantity of the admixture used and the mix proportions, for a normal concrete, the additional air due to water reducing admixtures may be as high as 5% (air-entraining WRA) and as low as 0.25% (sodium melamine sulfonate formaldehyde) [26].

Water Reduction: WRA and HRWRA are commonly used to reduce the water content of a concrete mix with a specified workability. The reduction in water content allows higher strength and durability characteristics or results in a more economical mix due to decreased cement content for a specified strength.

Amount of water reduction depends on:

(i) aggregate-cement ratio,

(ii) required workability,

(iii) addition level, and,

(iv) chemical composition of the cement.

Hydroxylated polymers and hydroxycarboxylic acid based WRA are preferred for low aggregate:cement ratios (rich concretes) whereas lignosulfonate-based WRA are more effective for high aggregate:cement ratios (leaner concretes) [26]. The higher workability results in a greater reduction in water:cement ratio upon WRA or HRWRA incorporation. As the amount of admixture used increases, water reduction also increases. Although the effect of the chemical composition of cement on the water reduction upon WRA use is not yet fully investigated, there is some evidence that water reduction decreases with increasing tricalcium aluminate or alkali content of the cement when lignosulfonate type WRA are used. Other types of WRA are not very much dependent on cement composition [26].

5.2.4.4 Effects of WRA on the Properties of Hardened Concrete

Specific Gravity: WRA and HRWRA increase the specific gravity of concrete provided that they do not result in air-entrainment. Increases of 0.6-1.2% were recorded [27].

Porosity: The porosity of cement paste decreases with decreasing water:cement ratio. Therefore, concretes with or without WRA have similar porosities at a given water:cement ratio [23] whereas porosity is reduced by WRA or HRWRA incorporation to obtain a specified slump.

Permeability: Due to the reduction in water:cement ratio, the permeability of concrete is reduced by using WRA or HRWRA. **Figure 5.11** illustrates that feature for a concrete with a given cement content and slump value when a commercial hydroxylated polymer is incorporated [28].

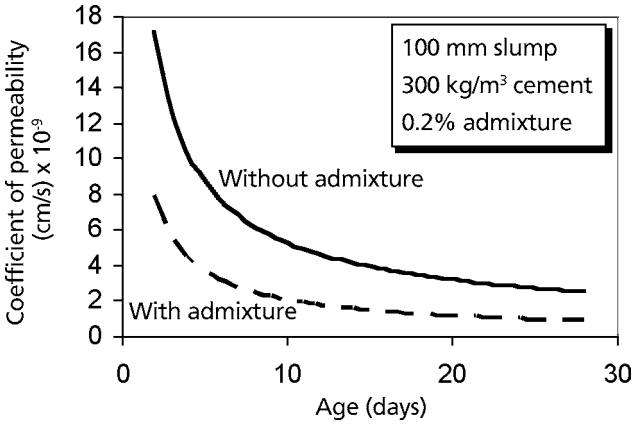


Figure 5.11 Permeability of concretes at a specified slump with and without hydroxylated polymer as WRA [28]

Strength: The compressive strength of concretes containing WRA or HRWRA follows the same rule as that of concrete without admixtures and is basically a function of water:cement ratio. Therefore, use of these materials for workability increase results in similar compressive strengths for a specified water:cement ratio. Reduction in water content for a specified workability results in higher compressive strength than the control concretes without admixtures. The relationship between compressive, tensile and flexural strength values does not change by using water reducing agents.

Modulus of Elasticity: There is no significant difference between concretes containing water reducing admixtures and control concretes without admixture.

Durability Aspects: The ability of concrete to resist external and internal aggressive effects depends on many parameters. However, permeability may be considered as an index to the durability. Since the permeability of concrete is reduced by water reducing admixtures for a specified workability, it can be stated that these admixtures have positive effects on freezing-thawing resistance, sulfate resistance, reinforcement corrosion, resistance to acid attack and resistance to expansion caused by alkali-silica reaction by reducing the ingress of aggressive liquids, gases and moisture into concrete.

Shrinkage and Creep: Results of several drying shrinkage tests on concretes with and without water reducing admixtures indicated that these admixtures have little or no detrimental effect [23, 28] although direct addition of water reducing admixtures to increase the workability increases the shrinkage [26]. A similar discussion holds true for the creep of concrete, too.

It is generally agreed that the shrinkage and creep of admixture-incorporated concretes follow the same mechanism, obey the same rules and are affected by the same parameters as the concretes without admixtures.

5.2.5 Polymeric Fibres in Fibre Reinforced Concrete

Concrete containing fibres is called fibre reinforced concrete. Fibres of various shapes and sizes produced from steel, plastic, carbon, glass and natural materials are used [29]. Polymeric fibres in fibre reinforced concrete include PA, polyester, PE, PP, polyolefins and Rayon among which PP is the most widely used. PP fibres are manufactured by drawing the polymer into thin film sheets, which are then slit to produce fine fibres. They come in three different configurations as monofilaments, collated bundles or continuous films. Although monofilaments disperse evenly in concrete, their handling is difficult. Collated bundles also disperse evenly in concrete and they are easier to handle. Continuous films are placed in forms prior to concrete pouring. The advantage of PP

fibres for use in concrete is due to their unique properties such as stability in alkaline environment, relatively higher melting point, and low cost.

Polymeric fibres can be used as primary reinforcement as mesh or fabric up to 10% by volume. However, they are commonly used in low volumes (<1.5%) as secondary reinforcement against plastic shrinkage cracking. They do not have a significant effect on the strength of concrete, but after the matrix has cracked, they provide some residual strength and resistance to crack propagation by bridging the cracks until they are pulled out or ruptured.

Adding fibres to concrete reduces the workability and the loss of workability is proportional to the volume concentration of the fibres. To compensate for this, WRA or HRWRA may be used [29]. Impact resistance, flexural fatigue resistance, and resistance to surface deterioration is increased by fibre reinforcement.

5.3 Use of Polymeric Materials in Repair and Strengthening of Structures

Uğur Polat

Historically, civil engineering is known to be a field of engineering which is conservative in the use of technological materials. An important part of the reason for this reliance on the either natural or close to naturally available traditional materials stems from the need for widespread availability and low cost for the construction materials to fulfill the very basic needs of man for shelter. Currently, steel may be considered as the most technological and widely used construction material. Nevertheless, in the past few decades, the civil engineers have been in constant search for alternatives to steel to alleviate the high costs of repair and maintenance of structures damaged by corrosion or natural events such as earthquakes and upgrading those in need of increased strength for heavier use. The lightweight, excellent durability and fatigue behaviour, easy handling and the high tensile strength of fibre-reinforced plastic (FRP) composites coupled with significant drop in their prices starting from mid-1990s have attracted the attention of civil engineers worldwide. An extensive review on the use of FRP composites in repair and strengthening of reinforced concrete (RC) structures can be found in [30].

5.3.1 Types of FRP Composites

FRP composites are a laminate structure such that each lamina contains an arrangement of unidirectional fibres embedded in a thin layer of polymer matrix material. The fibres provide the strength and stiffness and the matrix binds and protects the fibres and transfers the stresses between them. Fibres used in FRP composites for civil engineering applications are continuous or long fibres, which are approximately 5-20 μm in diameter. Continuous

fibres that are appropriate for civil engineering structures are carbon fibres (CF), aromatic polyamide or simply aramid fibres (AF) and glass fibres (GF).

CF are classified into two types based on the precursor raw material. One type is refined petroleum or coal pitch, which is passed through a thin nozzle and stabilised by heating. This type of CF is known as *pitch-type* fibre. The other type, which is more common, is polyacrylonitrile (PAN) fibres that are carbonised by burning at elevated temperatures and commonly known as *PAN-type* fibres. Both types of CF are a collection of imperfect black lead micro crystals. The diameter of pitch-type CF is approximately 9-18 μm and that of PAN-type CF is 5-8 μm. CF are known for their high strength, high modulus, high fatigue performance, and excellent moisture and chemical resistance.

AF used in the construction industry are better known by the trade names Kevlar and Twaron. Each is a family of fibre types rather than a particular one. AF are approximately 12 μm in diameter. They have high strength and fatigue performance, intermediate modulus, good moisture and chemical resistance, and well known for their excellent impact resistance.

GF are basically classified into two types: electrical or simply E-glass fibres and alkali resistant AR-glass fibres. E-glass fibres contain high levels of boric acid and aluminate, which lowers their alkali resistance, thus restricting their use in concrete structures. With the intention of preventing glass fibres from being eroded by cement system alkalinity, AR-glass fibres are obtained by the addition of zirconium. They are characterised by their high strength, low modulus, low moisture and chemical resistance, and low cost. A major drawback to their use as a construction material is their high rate of sensitivity to sustained loads under which they fail by creep rupture.

FRP composites are formed by embedding continuous fibres in a resin matrix, which binds the fibres together. Depending on the fibres used, FRP composites used in structural applications are classified into three basic types: carbon-fibre-reinforced polymer (CFRP) composites, glass-fibre-reinforced polymer (GFRP) composites, and aramid-fibre-reinforced polymer (AFRP) composites. Epoxy resins, polyester resins and vinyl ester resins are the common resins. However, epoxy resins are preferred and more common for structural applications. A general background on the composition of these materials and their mechanical properties can be found in the *State-of-the Art Report of ACI 440R-96* [31]

5.3.2 Methods of Forming FRP Composites

Fibres appropriate for civil engineering applications are available in three major formats: continuous or chopped strands, woven or unwoven fabrics (sheets) and pre-impregnated forms. Commercially available fibres are produced in the form of spooled strands.

They are later processed into other formats in secondary operations. The size of the fibre tow bundle can range from 1000 filaments (1K) to more than 200K. Generally, commercial-grade fibres appropriate for civil engineering applications have 48K or larger filament counts.

Two common methods of forming FRP composites are used in structural applications. The first method involves the impregnation of reinforcing fibres by *in situ* application of resin to either a woven fabric or a unidirectional tow sheet. This approach, which is referred to as the wet lay-up method, is the most commonly used scheme due to its versatility in site applications. The second method is the prefabrication of FRP composites in various forms (**Figure 5.12**). In this method FRP plates or other structural shapes with constant cross-sectional dimensions are obtained through a process known as pultrusion. First, the continuous fibres in roving or mat/roving form are drawn through a resin bath to coat each fibre with resin mixture. The coated fibres are then assembled by a forming guide and then drawn through a heated die. Finally, the resin is cured by heat. Examples of pultruded FRP components for structural applications range from simple plates to structural profiles similar to steel sections, round or ribbed rebars, bolts and nuts, pre-stressing tendons, and complex floor deck systems. On a number of occasions, preformed FRP shells have been used to strengthen circular columns. The most appropriate manufacturing process for FRP cylindrical shells seems to be the filament winding in which resin-impregnated fibres are wound around a mandrel or directly on the column surface. Although, the wet lay-up method is more versatile on-site applications in terms of bonding to curved surfaces and wrapping around corners, the prefabrication allows

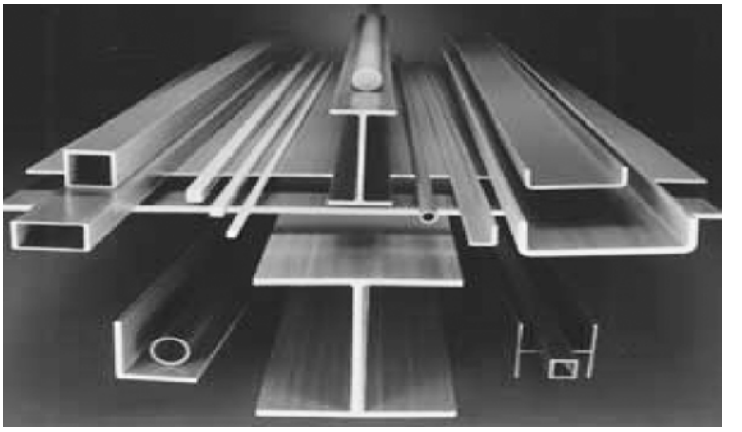


Figure 5.12 Various forms of prefabricated FRP composite structural shapes (Courtesy of Strongwel Inc.)

better quality control. In the wet lay-up process at the construction site, it is very difficult to prevent the fibres wrinkling, which effectively lowers their modulus of elasticity in the early stages of stressing. It should be noted that a similar effect is inherent in the two-way fabrics. Moreover, this method is sensitive to roughness of the surface, which can lead to premature debonding [32]. In the process of pultrusion, the fibres are stressed slightly to take up the slack before they are impregnated in a resin bath and kept so until the resin sets.

5.3.3 Mechanical Properties of FRP Composites

The mechanical properties of FRP composites depend on the type of fibre used in their production and the fibre content in the final product. These aspects are likely to vary between competing composite products since there is currently no agreed standard specification for their production. Therefore, all design must be based on the actual properties supplied by the manufacturer and laboratory test results.

In a typical FRP composite material used in structural applications, approximately 30 to 50% of the cross-section is the resin binder. However, the strength of the FRP reinforcement is mainly determined by the fibre content since the resin matrix contributes very little to the overall strength. Since the fibres make up only a portion of the composite section, the FRP strength is determined by the fibre content present in the section.

The most relevant mechanical properties of FRP for structural applications are the tensile strength, modulus of elasticity and the ultimate elongation at failure. Some representative values compiled from the literature are given in **Table 5.2** for high performance long fibres suitable for structural applications.

Table 5.2 Typical mechanical properties of CF, AF and GF used in structural applications

Classification of fibre	Tensile strength (MPa)	Modulus of elasticity (GPa)	Ultimate elongation (%)
CF (high strength)	4300-4900	230-240	1.50-2.10
CF (high modulus)	2740-5490	294-329	0.70-1.90
AF (high strength, high modulus)	3200-3600	124-130	2.40-4.60
GF (E-glass)	2400-3500	70-85	3.50-4.80

It should be noted that the fibre properties are based on short sample tests and are not representative of the actual strength or stiffness of the final FRP product. The strength of fibre bundles will be lower due to the higher probability of having micro defects in the long fibres, differential load sharing among fibres, the relatively lower strength of the resin, and inability of fibres to redistribute loads at high stress levels. As a result, the fibre stress in an FRP composite is, on the average, 30 to 40% lower than the constituent fibre strength. The modulus of elasticity of an FRP composite may be approximated by the rule of mixtures. If V_F is the volume fraction (percentage of the cross-section), and E_F is the modulus of elasticity of long fibres used, and E_R is the modulus of elasticity of the resin, the modulus of elasticity of FRP composite material, E_{FRP}, can be approximated as:

$$E_{FRP} = E_F V_F + E_R (1-V_F) \approx E_F V_F$$

Regardless of the type of fibres used, FRP materials display similar characteristic stress-strain behaviour: linear elastic up to ultimate strain followed by a brittle failure due to rupture, as shown in **Figure 5.13**.

This brittle behaviour of FRP composites has some important consequences in structural applications. First, it may limit the desirable ductile behaviour of RC members strengthened with FRP composites. Secondly, the redistribution of stresses is restricted due to this lack of ductility. Therefore, the design of structures bonded with FRP composites cannot follow the existing methods for RC structures by simply considering

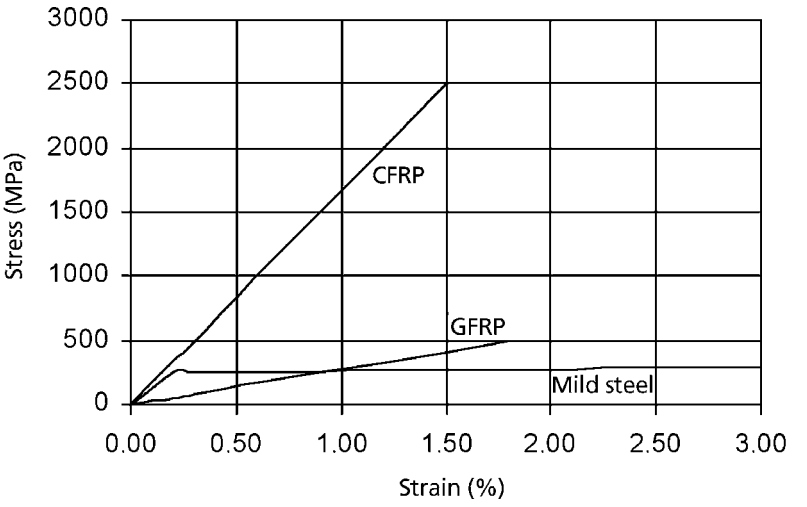


Figure 5.13 Typical stress-strain curves for FRP and mild steel

FRP as equivalent steel reinforcement. Existing design methods for RC structures need to be modified to take this brittle behaviour into account.

The deformability of FRP composites covers a good portion of the ductile range of steel. The concrete or masonry members reinforced with FRP continue to gain strength until rupture or compression failure of the concrete or masonry. However, as the FRP reinforcement ratios increase, the flexural members become progressively more and more brittle.

Another important property of FRP composites to be considered in the design process is their behaviour under shear. The shear strength of FRP composites is controlled by the behaviour and the shear strength of the binding resin, and the shear strength of resin which is relatively very low compared to the tensile strength of fibres. The actual strength of FRP composites is provided by the tensile strength of their constituent high performance fibres. Under shear forces, the high tensile stresses in one layer of fibres cannot be easily transferred to the adjacent layers as a result of a phenomenon known as shear lag caused by the relatively low shear strength of the binding resin. Consequently, the shear strength of FRP composites is relatively low compared to their tensile strength. For example, the steel shear strength is about 45% of its tensile strength while the FRP shear strength is often less than 10% of its tensile strength. This behaviour of FRP composites under shear must be taken into account in such cases as thick or deep FRP components when the stresses are applied on one face parallel to fibre direction or large diameter rods used as a rebar in RC components in which the axial stress capacity of FRP reinforcement drops rapidly with the increasing bar diameter [33].

A large number of tests have shown that the creep strength of CFRP is far superior to that of other fibre composites. In a creep test performed on CFRP rods under alternating load, no failure was observed in the rods up to a stress level of 70% of their short-term tensile strength after 10,000 hours [34]. In another experimental study, a creep strength of 79% of their short-term tensile strength is extrapolated for CFRP rods for a period of 50 years [35].

CFRP composites also have very high fatigue strength. In tests conducted with maximum stresses of up to 85% of their short-term tensile strength and amplitudes of up to 1,000 MPa, more than 4×10^5 load cycles were reached [36]. No fatigue failure and, in the subsequent tensile tests, no reduction in the tensile strength was observed of CFRP rods embedded in concrete after 4×10^5 load cycles with an amplitude range of 5-50% of their short-term tensile strength and a frequency of 0.5 Hz [37].

All three types of FRP composites used in construction have relatively very low coefficients of thermal expansion. It is nearly zero for CFRP in the fibre direction and AFRP even has

a negative coefficient of thermal expansion. Both theoretical and experimental studies, however, show that the thermal incompatibility between these FRP composites and the concrete substrate do not cause any serious damage to the bond between them within practical limits of temperature variation [38]. However, a real problem is to be expected at elevated temperatures approaching the glass transition temperature (T_g) of the epoxy used to bond the FRP composites to concrete surface. Typical T_g for epoxy is around 80 °C, above that the bond performance degrades very rapidly and practically disappears.

5.3.4 Bond Strength of FRP-to-Concrete Joints

RC structures are strengthened by externally bonding FRP plates and sheets to its members using epoxy resin. For the externally bonded FRP to be effective in increasing the load-carrying capacity of the structure, effective stress transfer between the FRP composite and the concrete is essential. The bond strength of FRP-to-concrete joints is a major limiting factor in exploiting the high strength of FRP composites for structural upgrading.

There is a considerable amount of experimental [39-43] and analytical [44-46] work reported in the literature on the bond strength of FRP-to-concrete joints. Based on the experimental results and observations made during the experiments on RC beams and slabs strengthened for flexure, the types of bond failures can be broadly classified into two main categories: *crack-induced interfacial debonding* and the *end-zone interfacial debonding*. In RC members subjected to bending, formation of flexural cracks is inevitable as the flexural capacity of the member is approached. Once such cracks are formed, the parts of FRP plate under the cracks are highly stressed. These stresses are transferred to the concrete, which causes a concentration of shear stresses in the interface eventually leading to bond failure of the FRP-to-concrete joints under the cracks. This interfacial separation progresses towards the less stressed regions as shown in **Figure 5.14(a, b)**. On the other hand, high interfacial stresses also build up in the end zones of the FRP-to-concrete joints. Since the level of axial stress in the FRP plate is low near the ends, the stresses normal to the interface layer (peeling stresses) cause a premature bond failure by separation of the FRP plate from the concrete surface (**Figure 5.14(c)**). The separation of the concrete cover is also possible in the end zones, as shown in **Figure 5.14(d)**, in cases when the concrete strength is low or when the cover concrete is on the verge of spalling (breaking into chips) as a result of corrosion in the steel rebars. In the literature, this type of failure is sometimes referred to as *concrete cover rip-off failure*, *concrete cover delamination*, and *concrete cover separation*. Therefore, some extra measures are necessary to anchor the externally bonded FRP plates in these end zones.

For FRP plates or sheets bonded to a concrete substrate, there is an effective bond length beyond which any increase in the bonded length cannot increase the total load the bonded

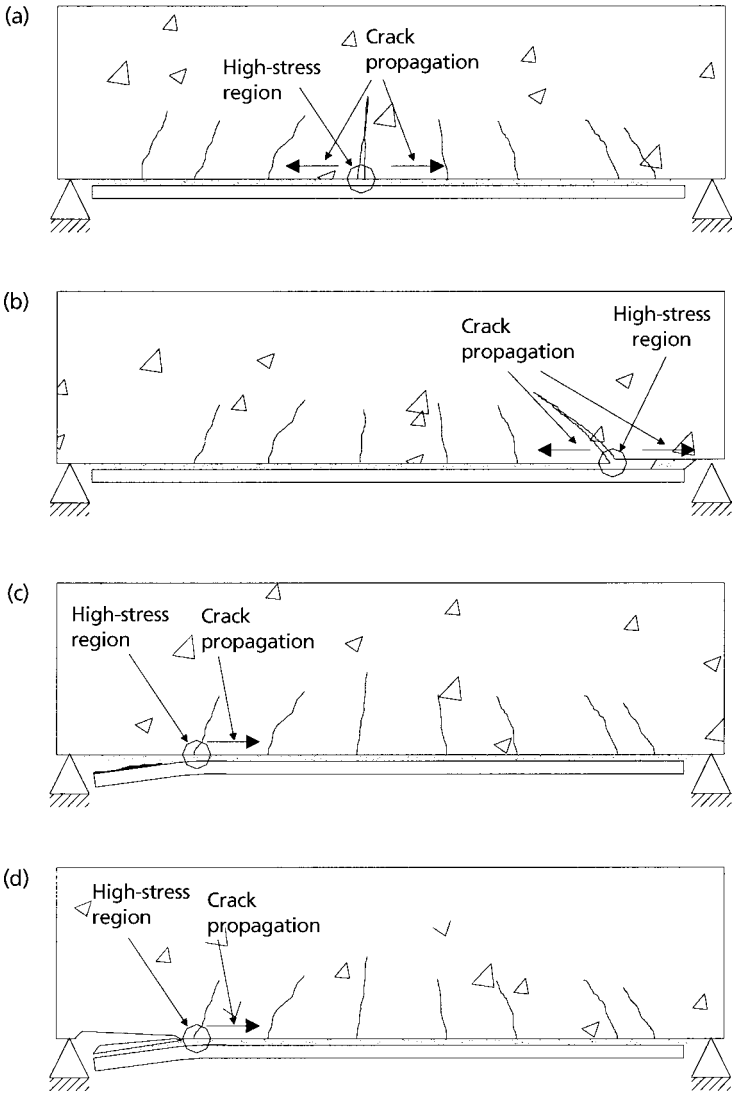


Figure 5.14 Bond failure modes of FRP-to-concrete joints: (a) flexural crack-induced interfacial debonding; (b) shear crack-induced interfacial debonding; (c) end-zone interfacial debonding; (d) end-zone interfacial debonding accompanied by concrete cover separation.

FRP is able to carry. In this sense, the bond behaviour of FRP-to-concrete is essentially different to the behaviour of the steel rebar-to-concrete bond.

5.3.5 Bond Strength Models

Numerous bond strength models have been proposed in the literature in recent years. Some of these are simply empirical models based on the regression of test data and some others are based on the principles of fracture mechanics. In all models, the ultimate goal is to determine the effective bond length, L_e, and the bond strength, P_u, of the FRP-to-concrete joint as a function of the strength of concrete substrate and mechanical and geometric properties of FRP composite. A review of the major bond strength models available in the literature and the assessment of their performance when applied to test results is given in [30].

A recent bond strength model proposed by Chen and Teng [47] combines the fracture mechanics analysis with experimental data and provides a better prediction of the basic parameters L_e and P_u. The model is a modified form of the model originally proposed by Yuan and Wu [45] and Yuan and co-workers [46] and based on a shear-slip behaviour of FRP plate to concrete as shown in **Figure 5.15**. The critical slip values of d_1 at peak shear stress and d_f at failure are taken as 0.02 mm and 0.2 mm, respectively, and the following forms are proposed for L_e and P_u:

$$L_e = \sqrt{\frac{E_p t_p}{\sqrt{f_c'}}} \tag{5.1}$$

$$P_u = 0.427 \beta_p \beta_L \sqrt{f_c'}\, b_p L_e \tag{5.2}$$

where

$$\beta_p = \sqrt{\frac{2 - b_p / b_c}{1 + b_p / b_c}}$$

$$\beta_L = \begin{cases} 1 & \text{if } L \geq L_e \\ \sin\left[\pi L / (2L_e)\right] & \text{if } L < L_e \end{cases}$$

In Equations 5.1 and 5.2, b_p and b_c are the widths in mm of the bonded plate and the concrete surface, respectively, t_p is the plate thickness in mm, E_p is the FRP plate modulus of elasticity in MPa, and f_c' is the concrete compressive strength in MPa.

It should be noted that this model is based on the mechanics of idealised joints and the analysis of some experimental results of simple shear tests. Certain modifications may be necessary when the model is applied in the presence of cracking activity in the RC member since the stress state in the case of crack-induced interfacial debonding situation is different than the stress state assumed in the derivation of this model.

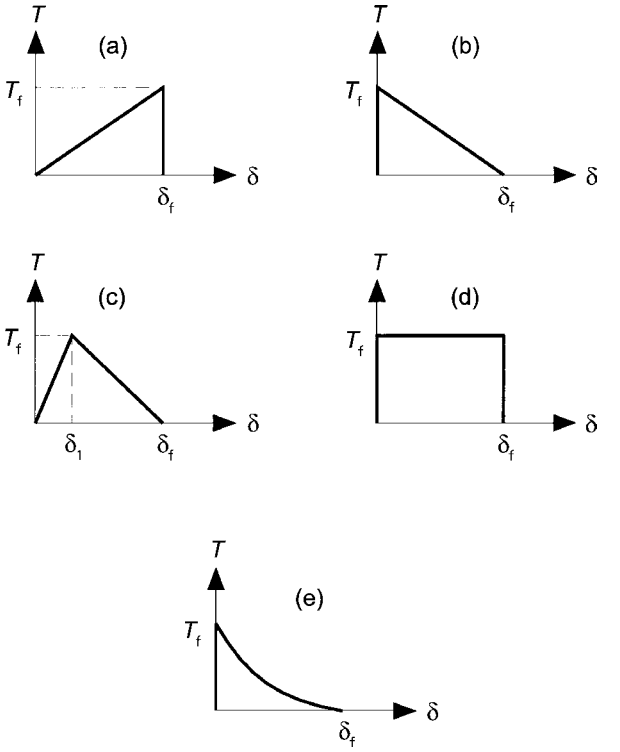


Figure 5.15 Shear-slip models for FRP-to-concrete bonded joints [45]

5.3.6 Flexural Strengthening of RC Beams

The research on the potential use of FRP composites in structural strengthening was first started for the flexural strengthening of RC beams. Prior to this research on FRP plate bonding, a considerable amount of research had already accumulated on steel plate bonding for flexural strengthening of RC beams and much of what was learnt in this research is relevant to FRP plate bonding.

Flexural strengthening of a simply supported RC beam using FRP composites is generally carried out by bonding an FRP plate to its soffit. The FRP plate may be prefabricated or it may be constructed on site by a wet lay-up process. The plate may be prestressed in an effort to control the deflection, flexural cracking and crack widths. FRP composites have high tensile strength and pre-stressing leads to more efficient use of them since a prestressed FRP is more likely to reach its ultimate tensile strength at failure. Direct application of a pre-stressing force to the plate may be difficult and requires special equipment.

However, a similar pre-stressing effect can be accomplished by bonding the FRP without the presence of any service loads on the beam or even by negative loading of the RC beam before the FRP bonding process. A detailed review of existing research on RC beams strengthened with prestressed FRP soffit plates is given by Hollaway and Leeming [48].

To prevent the end-zone debonding of the FRP soffit plate, special anchorage schemes are used. Relatively rigid steel plates placed over FRP plate and epoxy bonded to both the plate and the RC member surface or the use of U-shaped FRP strips formed by a wet lay-up process are the common types of end anchorage (**Figure 5.16**).

Until very recently, the most pultruded FRP plates on the market were unidirectional (UD). However, a new generation of bi-directional (BD) pultruded FRP plates is now available which make it possible to anchor the FRP soffit plates directly onto the RC member surface by anchor bolts. A detailed summary of different anchorage schemes and experimental results are given by Hollaway and Mays [49].

In practical applications, mechanical end-zone anchorage of the FRP plate must be considered whenever possible. In some practical situations, end-zone anchorage in the form of FRP U strips may not be possible or effective as in the case of wide and/or shallow beams.

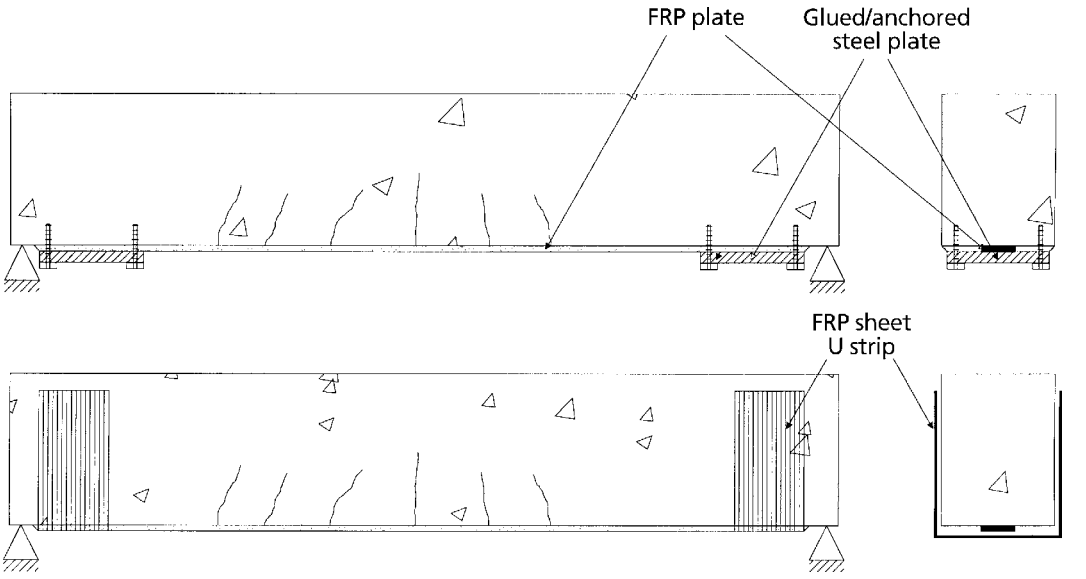


Figure 5.16 Anchorage schemes to prevent premature end-zone debonding

The risk of debonding can be reduced by a proper preparation of both the concrete and the FRP surfaces and the use of a better quality adhesive for bonding. It is important to have a clean and smooth concrete surface to utilise the high strength of the FRP to a better extent. It is even more so in the case of wet lay-up process of forming a thin layer of FRP since their profile closely follows the uneven concrete surface. Under tension, this thin and flexible layer of FRP tries to straighten itself. This, in turn, causes interfacial peeling stresses to develop and eventually leads to premature debonding in the concrete adjacent to the adhesive-to-concrete interface [32]. Another point to observe in the surface preparation phase is the treatment of any existing cracks of the RC member. Such cracks promote the crack-induced debonding and must be filled by a proper procedure, for instance by epoxy injection, before bonding FRP on to the surface. Failure can also occur at the FRP-to-adhesive interface with the pultruded FRP plates if the surface of the plate is not properly prepared. The new generation of pultruded FRP plates has a textured surface to increase the bond capacity and comes with a clean surface covered with a protective film. The film is peeled off on the site just before the application.

Strong adhesives are available for FRP plate bonding, and their strengths are, in general, higher than that of concrete. Therefore, failure in the adhesive layer is, normally, not expected and very rare. However, the use of a substandard adhesive or its improper application may result in an unexpected failure within the adhesive layer. Epoxy is the most commonly used adhesive for bonding FRP to concrete surface. Insufficient mixing of its components and/or mixing incorrect proportions of the raw materials on the construction site is a serious potential source for obtaining a substandard adhesive. Special attention must be paid to this point when a small amount of epoxy is needed while it is available in larger packages.

5.3.7 Shear Strengthening of RC Beams

Fibres running longitudinally along a beam do not make a significant contribution to the shear strength but they are helpful in limiting the shear crack width. Therefore, it is obvious that the longitudinal FRP bonded to the sides of a beam is not effective for shear strengthening [50, 51]. Various FRP bonding schemes have been used to increase the shear capacity of RC beams. Bonding FRP to the sides only is the easiest but the least effective and is more vulnerable to debonding. The fibres may be oriented so as to better control the shear cracks. Considering the possibility of reversed cyclic loadings, the fibres may also be oriented in two or even three directions. A better side-bonding alternative is the use of FRP sheet U jackets (sides + tension face) formed by a wet lay-up process. These are less vulnerable to debonding provided the beam depth is sufficient to provide a good bond length. The U jackets may be formed as intermittent strips or it may be formed by continuous sheets as shown in **Figure 5.17**. Another advantage of U jacketing is that they also act as mechanical anchors for the flexural FRP reinforcement.

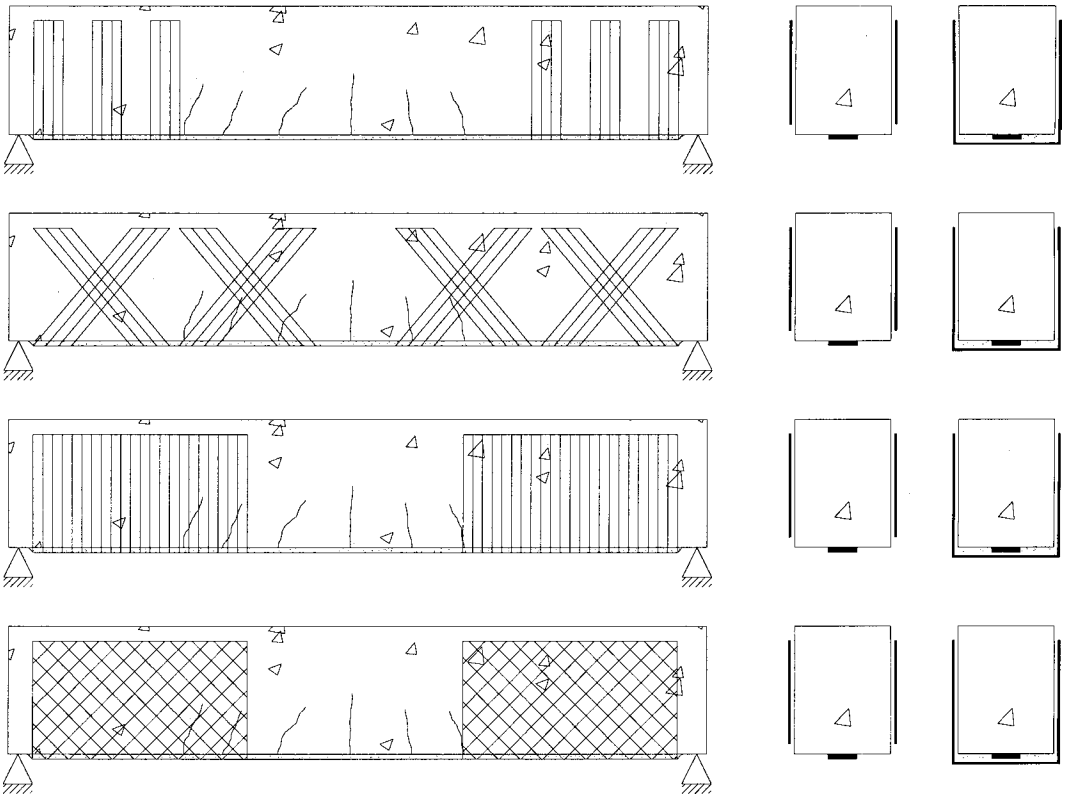


Figure 5.17 Various schemes for FRP shear strengthening

Two major modes of failure have been observed in experiments on RC beams strengthened for shear with FRP composites. These are the shear failure with or without FRP rupture, and premature failure by FRP debonding. Failures with or without FRP rupture are essentially the same and signify the effective use of the FRP strength if the corners are properly rounded to prevent stress concentrations. Premature failure by end-zone debonding of FRP can be delayed or even prevented by using some sort of supplementary anchoring of FRP at the end zones by, for example, steel plates and anchor bolts (**Figure 5.18**).

The idea in this scheme is to arrest the required anchorage force in the end zone by first transferring it to the steel plate glued over the FRP and then anchoring it to concrete base by anchor bolts and as contact stresses between the plate and the concrete base.

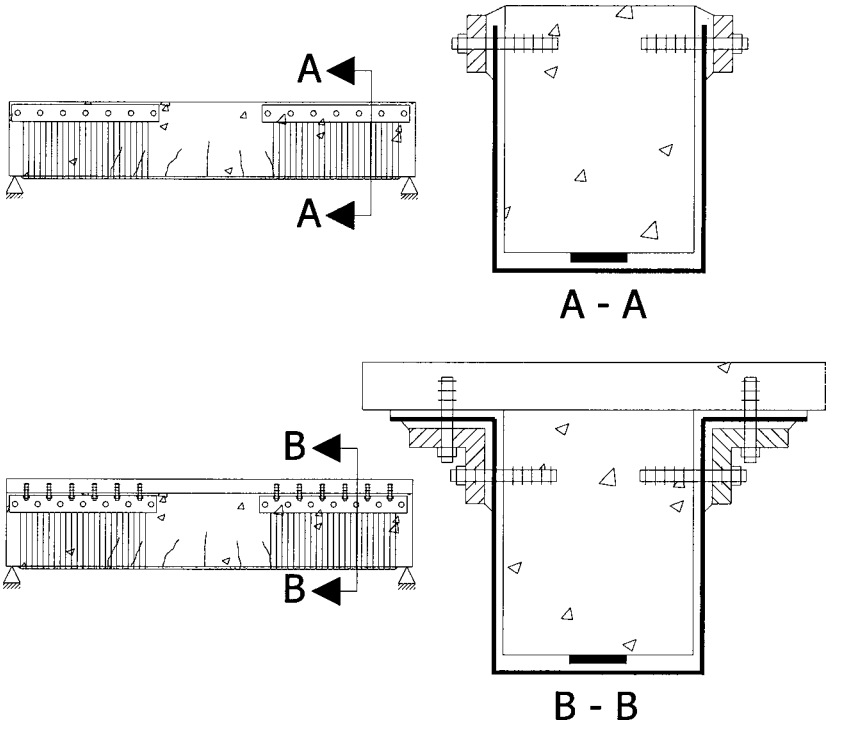


Figure 5.18 End-zone anchoring of FRP by steel plates and anchor bolts

5.3.8 Strengthening of RC Slabs

As a flexural member, the behaviour of one-way slabs is very similar to flexural behaviour of beams and, as far as the FRP reinforcement is concerned, the behaviour of two-way slabs can be taken as uncoupled bending in two orthogonal directions. It is probably for this reason that there is much less work reported in the literature on the flexural strengthening of RC slabs using FRP composites.

The basic procedure of flexural strengthening of slabs using FRP composites is to bond FRP on the tension face of the slab. This bonding of FRP can be in the form of strips (**Figure 5.19**) or the entire surface of the slab can be covered with FRP sheets. However, FRP sheets covering the entire surface of the slab makes it difficult to control the bond quality and may increase the risk of bond deterioration by blocking the free movement of moisture out of the bond surface [52]. For a given amount of FRP material to be bonded to the slab surface, applying it in the form of strips rather than covering the whole surface is more desirable. Similarly, the use of less number of wider strips as

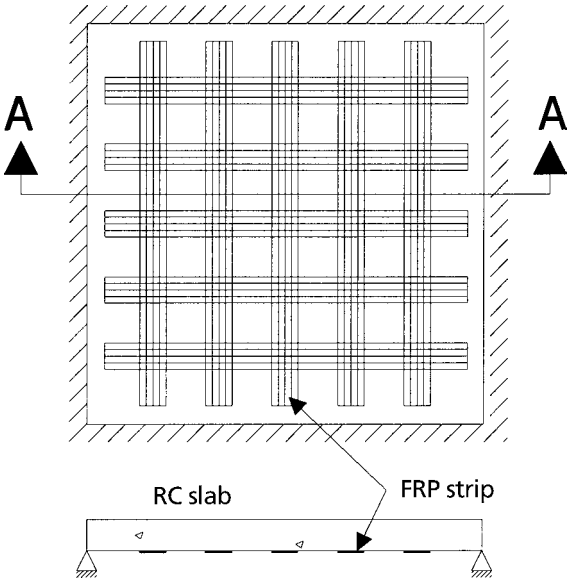


Figure 5.19 A two-way slab bonded with FRP strips for span moment.

opposed to increased number of narrow strips as the former offers a larger contact area between the slab and the FRP and thus reduces the risk of debonding failures.

A recent study by Zhang and co-workers [53] shows that two-way slabs bonded with a steel plate in the central region and subjected to central point loads fails by formation of yield lines around the perimeter of the bonded plate and along the diagonal lines in the unstrengthened part of the slab. Slabs bonded with an equivalent amount of FRP can be expected to behave in a similar fashion. This observation suggests the idea of increasing the span moment capacity of slabs by changing its yield line pattern (failure mechanism) as postulated by the lower bound theorem of plasticity. Therefore, it is possible to increase the span moment capacity of slabs by strengthening part of it so as to push the yield line pattern away from the strengthened portion.

Strengthening RC slabs near the continuous support regions for negative moment presents an extra difficulty regarding the anchorage of FRP in these regions. The slabs are usually subject to the greatest bending moment over the continuous supports and the FRP strips or sheets cannot be terminated before ensuring proper anchorage. The difficulty arises when there is a wall over the support, which is often the case, or an upturned edge beam. The simple idea of bending the FRP strips or sheets over the edge surface in a wet lay-up process was found to be ineffective in a test in which debonding of FRP from the wall

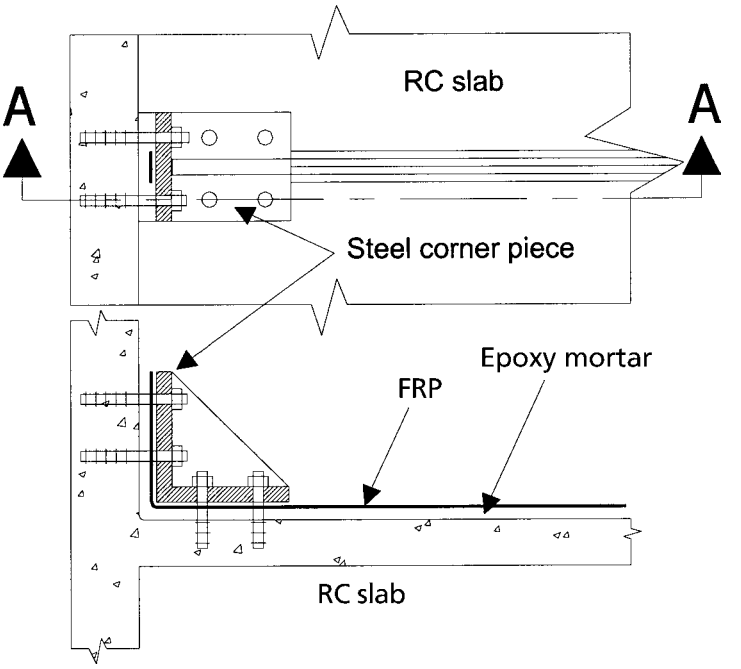


Figure 5.20 FRP anchorage for wall-supported slabs

was observed while the stresses in the FRP were quite low [54]. Therefore, some sort of extra measure for end-zone anchorage is necessary for the effective and efficient use of FRP in such cases. One alternative solution to prevent this premature failure by end-zone debonding can be the use of steel plates glued over the FRP and anchored to the concrete base as shown in **Figure 5.20**. In this scheme, a part of the required anchorage force in the FRP is first transferred to the steel plate and then to the concrete base partly by anchor bolts and partly as shear stresses spread over a larger contact area of the steel plate with concrete base.

5.3.9 Strengthening of RC Columns

Details of FRP jacketing methods for columns are discussed in Section 5.3.2, so they are not repeated here.

There are basically three types of failure modes observed in existing RC columns with inadequate transverse reinforcements and/or seismic detailing. The first and the most critical

failure mode is the shear failure manifested by inclined cracking, cover-concrete spalling, and rupture or opening of the transverse reinforcement eventually leading to brittle failure of the column. The second column failure mode, usually encountered in structures when they are subjected to severe seismic forces, is the formation of plastic hinges at the column ends due to high flexural stresses. The high flexural effects at column ends cause crushing and spalling of the cover-concrete and buckling of the longitudinal rebars. This mode of failure is usually caused by the lack of sufficient confinement in these regions. Finally, column failure in the regions of lap splices at the lower ends and rebar cut-off areas due to insufficient splice length and/or confinement is also a common mode of failure.

Prior to early 1990s, constructing an additional shell around a deficient RC column in the form of a reinforced concrete cage or a grout-injected steel jacket was a common rehabilitation technique used by the engineers. In recent years, the use of FRP composites for the strengthening of RC columns has become increasingly popular among engineers and researchers [31, 55-57].

It is a well-established fact that lateral confinement of concrete can substantially enhance its compressive strength and ductility [58-61] and it is beneficial to controlling, delaying and, in some cases, even preventing all three modes of failure mentioned above. Therefore, the most common form of FRP strengthening of columns involves external wrapping of FRP sheets or straps around them.

Many researchers have studied the stress-strain behaviour of concrete confined with FRP composites. Enhancement in the compressive strength of concrete as a result of external wrapping of FRP was first demonstrated by Fardis and Khalili [62, 63]. Although the mechanical aspects of FRP confinement of concrete leading to an improvement in its behaviour is very similar to that of steel, there are some major differences between the two: One of the problems with FRP confinement of concrete is that the strength of FRP jacket cannot be fully utilised until the lateral strain in the confined concrete is very high. In some cases, the concrete will crush before the potential strength of FRP jacket is fully mobilised [65-67].

The idea of confining concrete by winding continuous resin-impregnated fibre strands around RC columns (filament winding) is another technique used for FRP strengthening of RC columns. In this process, an FRP jacket with controlled thickness, fibre direction and volume fraction can be obtained. This procedure is more appropriate for circular columns and usually, special computer-controlled winding machines are used for this purpose.

Existing RC columns can also be strengthened using prefabricated FRP shells. The shells are prefabricated under controlled conditions using fibre strands or sheets. They can be fabricated in half cylindrical or rectangular shells. They can also be fabricated in a closed form with a vertical slit so that they can be opened up and placed around the columns.

For the FRP confinement to be effective, a full contact between the column surface and the FRP shell is essential. This can be ensured by either bonding the shell directly on to the concrete surface using adhesives, or injecting cement grout or mortar into the space between the shell and the column.

Comparing the three approaches to column strengthening by FRP confinement of concrete, it is seen that external wrapping is by far the most commonly preferred approach mainly because of its flexibility in coping with different column shapes and ease in site handling.

Level of confinement provided by externally applied FRP shell depends on the shape of the column cross-section. Although it is very effective for circular and nearly circular columns, it is much less effective for rectangular columns especially if the aspect ratio is high. For rectangular columns, more effective confinement can be achieved by modifying the column section into a circular or elliptical shape before FRP jacketing [69-70]. Prefabricated and slightly oversized circular or elliptical shells can also be used for this purpose in which the FRP shell also functions as a permanent formwork for casting the additional concrete.

The confinement provided by externally applied FRP is normally passive in nature, in that the confining effect cannot be started before a significant axial deformation of the column is realised. However, the confinement provided by FRP can be made active by applying some pretension to fibres during external wrapping or filament winding process and filling the gap between the RC columns and the slightly oversized FRP jacket around them with expansive cement grout or pressure injected epoxy resin [68-70].

The rupture strains of FRP measured in recent tests on FRP-confined concrete cylinders are substantially below those from flat coupon tensile tests [71-73]. This discrepancy is attributed mainly to the curvature of the FRP jacket and the non-uniform deformation of concrete.

5.3.10 Strengthening of Masonry Walls and Infills

Unreinforced masonry buildings in which the masonry walls are the main load-bearing components make up a good portion of the existing building stock worldwide. Among masonry structures, historic monumental structures are exceptionally important since today's society looks at these old buildings as a reminder of the past and the interesting architectural practices of past generations. Masonry is a strong construction material under compression or gravity loads. However, the bond between mortar and the masonry block is normally quite low and does not provide comparable resistance to tensile, flexure,

and shear forces. Eventually, a need for strengthening such structures often arises as a result of deterioration, exceptional loadings and settlements. The use of FRP- based strengthening techniques comes in very handy since low-impact approaches based on non-intrusive methods are usually demanded for such structures [74].

Residential building types of masonry structures in seismic zones are often in need of upgrading against earthquake forces. This requires strengthening of the walls so as to increase their shear capacity. Experimental works reported in the literature [75, 76] reveal that shear strengthening of masonry walls using FRP composites is not as effective as their flexural strengthening. The main setback in this endeavour appears to be the effective anchoring of FRP near the wall boundaries and especially in the corner zones.

Another reason for strengthening masonry walls is non-structural. A wide spread use of natural gas in buildings and numerous terrorist activities that have surfaced in recent years have created a due concern that non-structural masonry walls in structures must be strengthened against blast effects of explosions to prevent injuries by wall debris. Conventional techniques of retrofit often add significant mass to the structure and

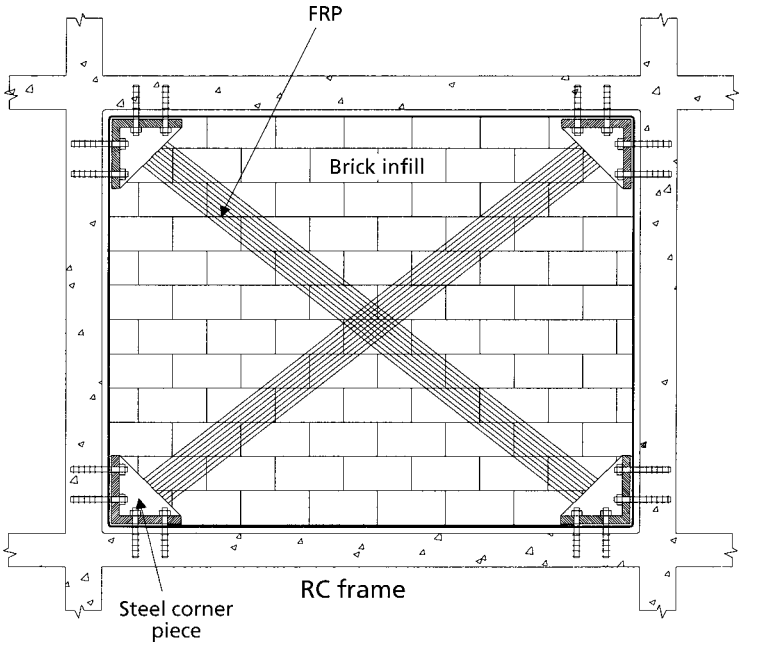


Figure 5.21 An alternative anchorage scheme of FRP to RC frame in an infill strengthening operation

adversely affect the aesthetics of the upgraded area besides being costly, disturbing to the occupants, and time-consuming. These disadvantages may be overcome by using FRP composites as reinforcing material [77]. Several investigations have indicated that flexural strength and ductility of un-reinforced masonry walls can be enhanced considerably by externally bonded FRP reinforcement [78, 79].

Masonry walls are normally used as non-structural partition walls in most of the RC frame type of building structures. In seismic zones, observations after earthquakes reveal that these non-structural walls play an important role in resisting the earthquake forces. Probably, the most exciting use of FRP composites for structural strengthening in seismic zones is the potential of strengthening some of these masonry infill walls against shear effects and, thus, turning them into lateral load-resisting shear walls for seismic upgrading. A major problem in this approach is to find an effective anchorage mechanism to transfer large forces in the FRP composite to RC frame at the joints. One such alternative is shown in **Figure 5.21**.

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6 Plastics and Plastics Composites: A Perspective on their Chemistry and Mechanics

Leyla Aras and Guneri Akovali

6.1 Chemistry of Plastics

It can be considered that the mid 20th century into the 21st century will be known as the age of synthetics; these are plastics, man-made fibres, synthetic rubbers, sealants, caulking compounds, composite materials and synthetic adhesives. In general, the properties of plastics are intermediate between those of fibres and elastomers with many overlapping properties, so, typical plastics may have cohesive energies higher than those of elastomers but lower than those of fibres. Thus plastics exhibit some flexibility and hardness with varying degrees of crystallinity.

Completely synthetic polymers, such as Bakelite, were first produced in 1909. Chemically Bakelite is phenol formaldehyde resin produced when phenol and the gas formaldehyde are combined in the presence of a catalyst. This product is used today in certain engineering applications. Now it is possible to adapt polymers and to create new ones which can be designed for specific functions. Polymers, together with metals and ceramics represent the essential engineering materials in the construction of buildings, household articles of all kinds, vehicles, engines, etc. The main factors responsible for the rapid growth of these engineering materials are [1]:

(a) The availability of basic raw materials: the sources of production are coal, oil, wood, agriculture and forest wastes

(b) The ensemble of technical properties specific for polymers: lightweight, chemical stability, elasticity, etc.

(c) Easy processing using techniques such as extrusion, thermoforming, injection moulding, calendering, casting, etc.

6.1.1 Molecular Weight

A polymer is a large molecule, i.e., a macromolecule consisting of a large number of repeating small, simple chemical units called monomers covalently bonded to form a

chain. Many of the distinctive properties of polymers are a consequence of the long chain lengths which account for the high molar masses of these substances. As a result, the accuracy of the measurements is much lower than for simple molecules.

Polymer samples exhibit polydispersity and the molar mass is an average depending on the particular method of measurement used. One of the most important characteristerics of these long chain molecules is their degree of polymerisation (DP), i.e., the number of mers (repeating units) in a given macromolecule (Equation 6.1) [1, 2].

$$\text{DP} = \frac{\text{MW of the polymer}}{\text{MW of the structural unit (mer)}} \tag{6.1}$$

Therefore, MW of polymer = monomer mass x DP

Polymer chains grow to different lengths during synthesis giving a product consisting of a mixture of long polymer chains of a range of molecular weights. That is why all natural and synthetic polymers are hetereogeneous with respect to the lengths of their chains.

Certain average values of molecular weight (MW) are used to characterise a polymer and these average values are obtained by several different methods. They are:

Number average molecular weight, $\overline{M}_n$:

$$\overline{M}_n = \frac{\sum_{i=1}^{n} n_i M_i}{\sum_{i=1}^{n} n_i} = \frac{\text{Weight of polymer sample}}{\text{Number of molecules existing in this sample}} \tag{6.2}$$

where (n_i = number of macromolecules in the fraction 'i' having the mean molecular mass M_i).

- Methods of measurement of $\overline{M}_n$ are:

  Osmotic pressure

  Boiling point elevation

  Freezing point depression

  Vapour pressure lowering

  For special type of polymers, end group analysis.

- Weight average molecular weight, $\overline{M}_w$:

$$\overline{M}_w = \frac{\sum_{i=1}^{n} n_i M_i^2}{\sum_{i=1}^{n} n_i M_i} \tag{6.3}$$

$\overline{M}_w$ is determined experimentally by light scattering, which depends on the size and the mass of the molecules.

- Z-average molecular weight, $\overline{M}_z$:

$\overline{M}_z$ is expressed mathematically as:

$$\overline{M}_z = \frac{\sum_{i=1}^{n} n_i M_i^3}{\sum_{i=1}^{n} n_i M_i^2} \tag{6.4}$$

- Viscosity average molecular weight, $\overline{M}_v$:

The Mark-Houwink equation defines the viscosity average molecular mass as:

$$[\eta] = K \bar{M}_v^{a} \tag{6.5}$$

where:

$[\eta]$ = intrinsic viscosity

k and a = constants which depend on the nature of polymer, temperature, and solvent.

$$[\eta] = \lim_{c \to 0} \eta_{sp} / c \tag{6.6}$$

$$\eta_{sp} = \eta_{rel-1} = \frac{\eta}{\eta_0} - 1 = \frac{\eta - \eta_0}{\eta_0} \tag{6.7}$$

where:

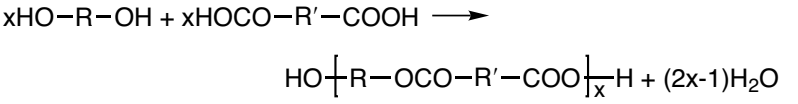
η_{sp} = specific viscosity
η_{rel} = relative viscosity
η = the viscosity of the solution
η_0 = the viscosity of the solvent
c = the concentration of the polymer in the solution (g/100 cm^3)

$\frac{M_w}{M_n}$ is used to determine the spread of the molecular weight distribution of the polymer that is the polydispersity and the ratio is called the heterogeneity index, (HI). HI is close to one for a narrow polydispersity, and it may increase to 3-10 for a broad molecular mass distribution.

6.1.2 Synthesis of Polymers

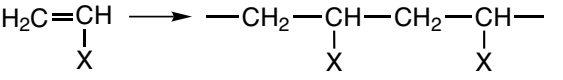
6.1.2.1 Condensation Polymerisation

Carothers in 1929 made the classical subdivision of polymers into two main groups, condensation and addition polymers. Condensation polymers, are characteristically formed by reactions involving the elimination of a small molecule, such as water, in each step. Polyester formation is a good example of this type of polymerisation. Bifunctional monomers react with each other with the elimination of water as shown in **Reaction 6.1**.



Reaction 6.1

In addition polymers, no loss of small molecules takes place. The most important group of addition polymers are synthesised from unsaturated vinyl monomers, see **Reaction 6.2**.



Reaction 6.2

Table 6.1 Distinguishing features of chain- and step-polymerisation mechanisms	
Chain polymerisation	**Step polymerisation**
Only growth reaction adds repeating units one at a time to the chain.	Any two molecular species present can react.
Monomer concentration decreases steadily throughout the reaction.	Monomer disappears early in reaction: at a DP 10, less than 1% monomer remains.
High polymer is formed at once. Polymer molecular weight changes little throughout the reaction.	Polymer molecular weight rises steadily throughout the reaction.
Long reaction times give high yields but affect molecular weight little.	Long reaction times are essential to obtain high molecular weights.
Reaction mixture contains only monomer, high polymer, and a very small amount of growing chains.	At any stage all molecular species are present in a calculable distribution.
DP: Degree of polymerisation	

Later in the 1950s, Mark classified polymerisation without considering the loss of a small molecule or type of inter unit linkage. To avoid confusion, he based his classification on the basis of mechanism and used step reaction and chain reaction where step-growth and chain-growth polymerisation are also very commonly used. **Table 6.1** summarises the main differences between chain and step polymerisation mechanisms [2-4].

Some examples of commercially important step-growth polymerisations together with non condensation step-growth polymerisations are illustrated in **Figure 6.1**.

6.1.2.2 Chain (Addition) Polymerisation

In this type of polymerisation an initiating molecule is required so that it can attack a monomer molecule to start the polymerisation. This initiating molecule may be a radical, anion or cation. Chain growth polymerisation is initiated by free-radical, anion or cation proceeded by three steps: initiation, propagation and termination. The chemical nature of the substituent group determines the mechanism.

- **Initiation**

Initiation in a free radical polymerisation consists of two steps.

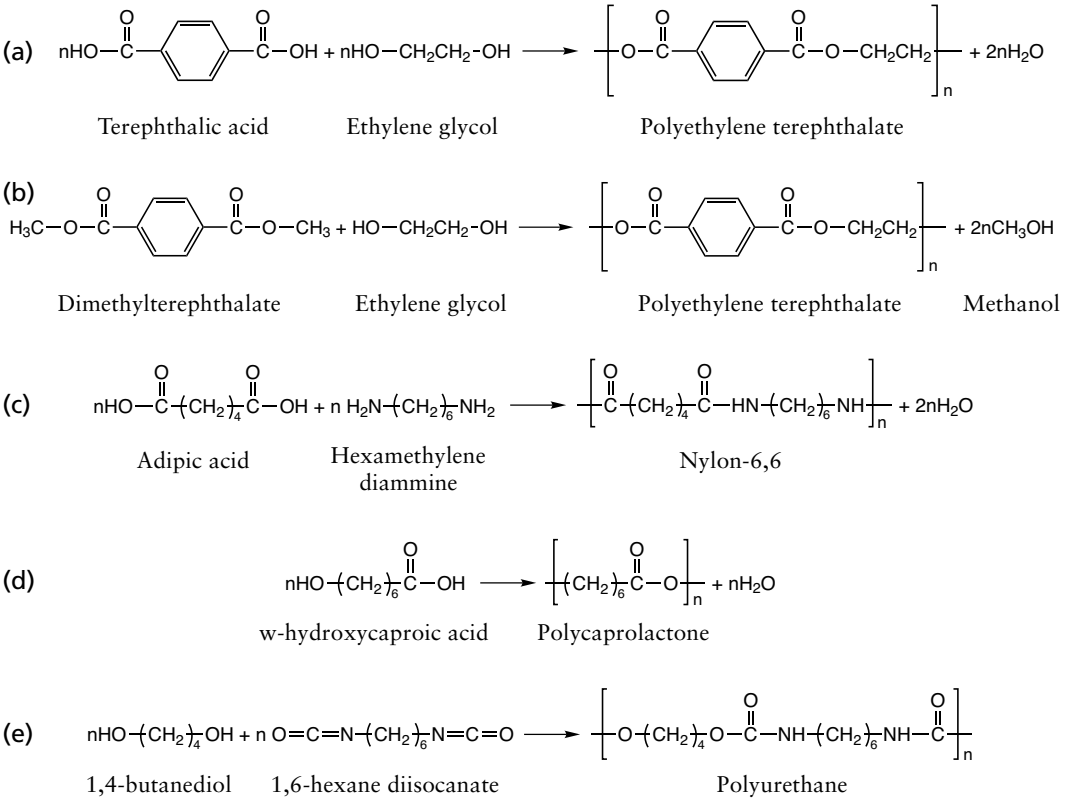


Figure 6.1 Examples of important condensation (a, b, c and d) and non-condensation (e) step-growth polymerisations. (a) Polyesterification. (b) Ester-interchange polymerisation. (c) Polyamidation. (d) Self-condensation of an A-B monomer. (e) Addition polymerisation of a polyurethane.

A dissociation of the initiator to form a radical species:

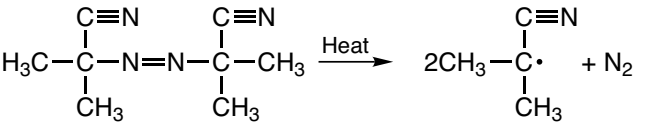
$$I — I \xrightarrow{k_d} 2I\cdot$$

where k_d is the dissociation rate constant, and

$$k_d = A \exp(-E_a / RT) \tag{6.8}$$

where E_a is the activation energy for dissociation and T is the temperature in Kelvin and R is the general gas constant. Although E_a is strongly dependent on temperature, dissociation rate constants for different initiators vary with the nature of the solvent used in solution polymerisation.

Some commonly used initiators for free-radical polymerisations include azo (-N=N-), disulfide (-S-S-) or peroxide (-O-O-) groups, (i.e., dissociation of 2,2′-azobis(isobutyro nitrile) which yields nitrogen and two cyanoisopropyl radicals), see **Reaction 6.3**.



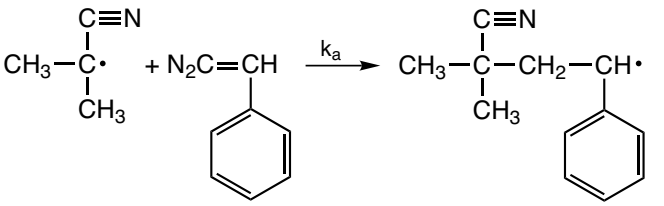
Reaction 6.3

- **Association**

A monomer molecule (M) is attached to the initiator radical:

$$I\cdot + M \xrightarrow{k_a} IM\cdot$$

where k_a is a rate constant for monomer association, and



where M is a (styrene) monomer.

- **Propagation**

In this step, additional monomer units are added to the initiated monomer species:

$$IM\cdot + M \xrightarrow{k_p} IMM\cdot$$
$$IM_X\cdot + M \xrightarrow{k_p} IM_XM\cdot$$

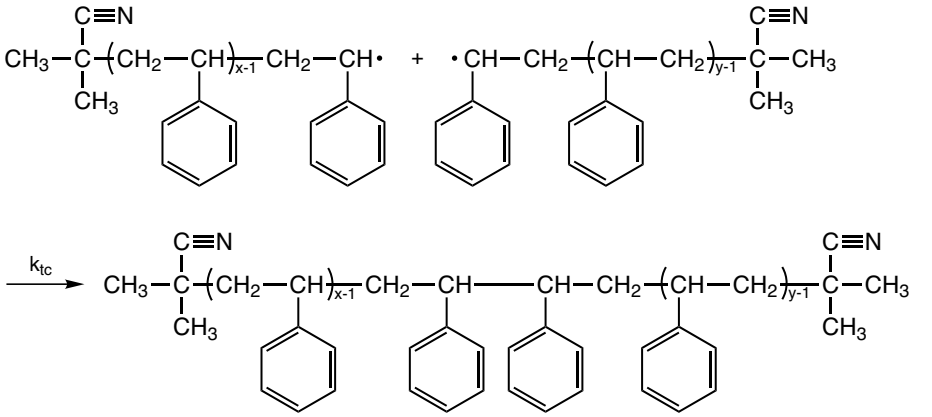
where k_p is propagation rate constant.

- **Termination**

Propagation will continue until some termination process occurs. Two termination mechanisms may take place:

Termination by combination

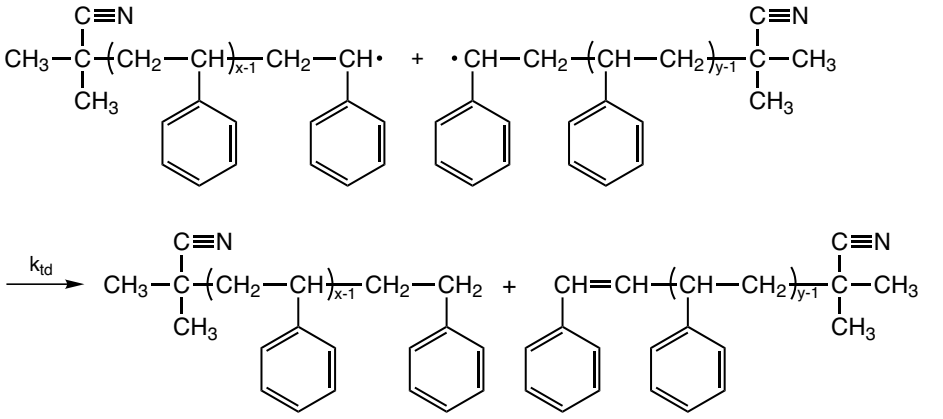
$$IM_{X-1}M\cdot + \cdot MM_{Y-1}I \xrightarrow{k_{tc}} IM_{X-1}M-MM_{Y-1}I$$



Here, x and y are arbitrary degrees of polymerisation.

Termination by disproportionation

$$IM_{X-1}M\cdot + \cdot MM_{Y-1}I \xrightarrow{k_{td}} IM_X + IM_Y$$



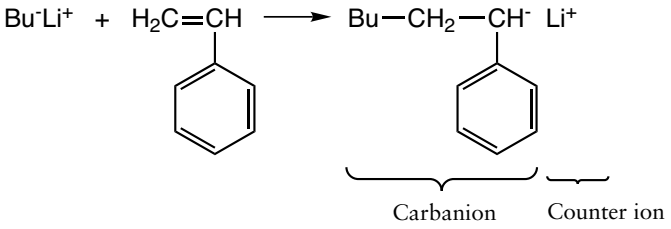
As seen from the termination reactions, cyanoisopropyl groups cap both ends of the chain in the case of termination by combination, one end of the chain is capped in termination by disproportionation.

In addition to termination by combination and disproportionation, chain transfer reaction also terminates a growing chain. Chain transfer occurs by hydrogen abstraction from an initiator, monomer, polymer or solvent molecule [2-4].

$$IM_{X-1}M\cdot + SH \xrightarrow{k_{tr}} IM_{X-1}MH + S\cdot$$

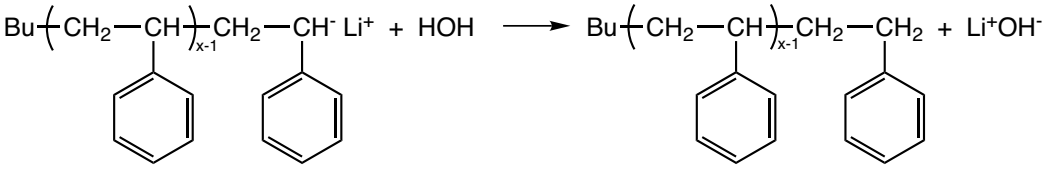
6.1.2.3 Anionic Polymerisation

Monomers with an electron withdrawing group can polymerise by an anionic pathway. The initiator in anionic polymerisation may be any strong nucleophile including Grignard reagents and other organometallic compounds like *n*-butyl (*n*-C_4H_9) lithium. Initiation of styrene is given as an example, see **Reaction 6.4**.



Reaction 6.4

Propagation takes place by insertion of additional styrene monomers between the carbanion and counterion. Under very pure conditions including the absence of water and oxygen, propagation can proceed indefinitely or until all the monomer is consumed. For this reason, anionic polymerisation is sometimes called 'living' polymerisation. In anionic polymerisation, termination occurs only by the deliberately added oxygen, carbon dioxide, methanol or water into the reaction medium as shown in **Reaction 6.5**.

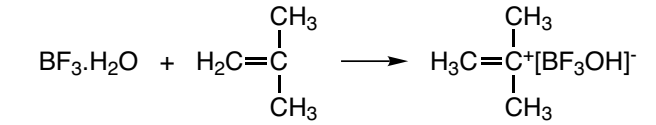


Reaction 6.5

In typical free radical polymerisation, polydispersity is above 2 and as high as 20. In anionic polymerisation, the absence of termination due to a living polymerisation, may cause very narrow molecular weight distribution with polydispersities as low as 1.06.

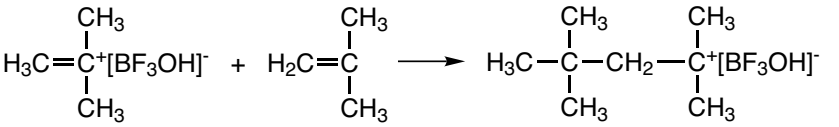
6.1.2.4 Cationic Polymerisation

Monomers with an electron donating group follow a cationic pathway. Unlike free radical and anionic polymerisations, initiation in cationic polymerisation uses a true catalyst that is restored at the end of the polymerisation and thus not incorporated into the terminated polymer-chain. A strong Lewis acid, such as H^+, BF_3 or $AlCl_3$ can be used as a catalyst. A cocatalyst, e.g., water, is also required to provide the actual proton source in some cases. Cationic polymerisation of isobutylene is given in **Reaction 6.6**.



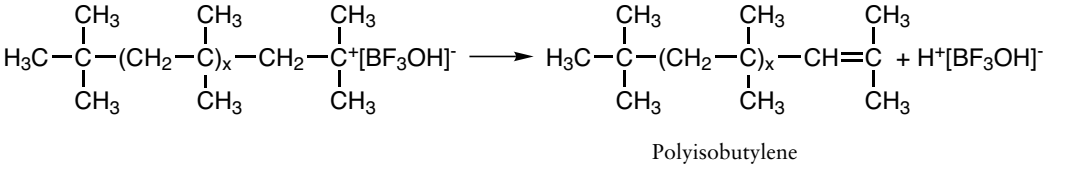
Reaction 6.6

Proton addition yields an isobutylenecarbonium ion. BF_3OH is the counterion or gegen ion. Propagation is as shown in **Reaction 6.7**.



Reaction 6.7

Termination is similar to anionic polymerisation termination and transfer to counter ion is represented in **Reaction 6.8**.



Reaction 6.8

Cationic polymerisations are usually conducted at low temperatures (–80 °C to –100 °C) in solution.

6.1.2.5 Copolymerisation

During a free radical copolymerisation involving two monomers, four separate propagation steps with four rate constants are possible:

$$1 \quad \sim M_1 \cdot + M_2 \xrightarrow{k_{11}} \sim M_1M_1 \cdot$$

$$2 \quad \sim M_1 \cdot + M_2 \xrightarrow{k_{12}} \sim M_1M_2 \cdot$$

$$3 \quad \sim M_2 \cdot + M_1 \xrightarrow{k_{21}} \sim M_2M_1 \cdot$$

$$4 \quad \sim M_2 \cdot + M_2 \xrightarrow{k_{22}} \sim M_2\mathbf{M}_2 \cdot$$

During a copolymerisation, it is important to be able to predict how copolymer composition varies as a function of comonomer reactivity and concentration at any time. The reactivity ratios are defined as $r_1 = k_{11}/k_{12}$ and $r_2 = k_{22}/k_{21}$ where r_1 and r_2 are reactivity ratios of monomer 1 and 2, respectively. The copolymer is random or ideal when $r_1 = r_2 = 1$, alternating when $r_1 = r_2 = 0$.

Ionic copolymerisation is also possible. An important example of an ionic copolymerisation is the triblock copolymer of styrene-butadiene-styrene (S-B-S), an example of a thermoplastic elastomer.

6.1.2.6 Emulsion Polymerisation

It is always convenient to control the heat evolved during polymerisation and this is achieved when the reaction takes place in a solvent. It is possible to control the heat transfer by solution, suspension and emulsion polymerisations [5]. A short discussion of emulsion polymerisation will be given next. In this polymerisation technique, the initiator must be soluble in water. A common initiator for this purpose is persulfate-ferrous initiator which yields a radical sulfate anion through the reaction shown in **Reaction 6.9**.

$$S_2O_8^{-2} + Fe^{+2} \longrightarrow Fe^{+3} + SO_4^{-2} + SO_4^{-} \cdot$$

Reaction 6.9

The essential ingredients for emulsion polymerisation are:

- Monomer
- Emulsifying agent
- Water
- Water soluble initiator
- Surfactant (normally an amphipathic long chain fatty acid salt with a hydrophilic 'head' and a hydrophobic 'tail')

Aggregates or micelles (0.1 to 0.3 μm long) are formed in water consisting of 50 to 100 molecules oriented with the tails inwards, creating an interior hydrocarbon environment and a hydrophilic surface of heads in contact with water. The concentration of micelles must exceed 'critical micelle concentration'. Radicals diffuse through the aqueous phase and penetrate both the micelles and the droplets. The polymerisation takes place in the micelle interior. **Figure 6.2** represents an emulsion polymerisation system.

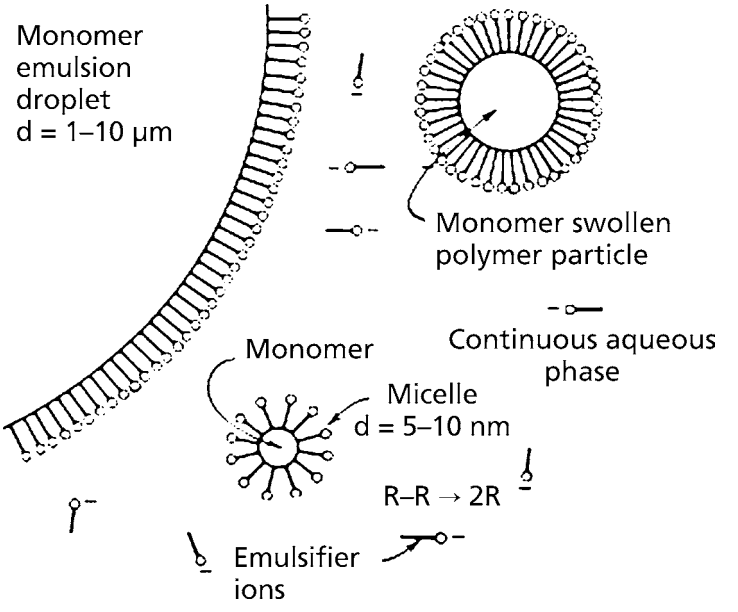


Figure 6.2 Schematic representation of a emulsion polymerisation system

6.1.3 Classification

There are many ways of classifying of polymers because of the diversity of function and structure found in the field of macromolecules. One way of doing this is shown in **Figure 6.3** [1, 2].

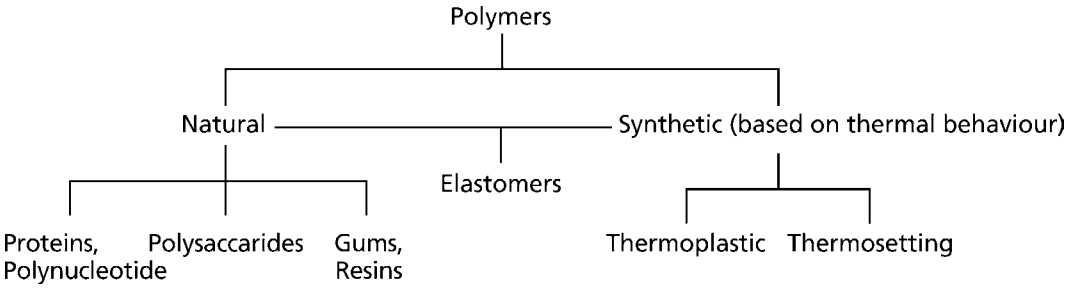


Figure 6.3 General Classification of Polymers

Synthetic polymers may be classified according to their:

- Monomer type
- Preparative techniques
- Polymer structure
- Physical properties
- Processing techniques
- End uses (associated with specific industries such as fibre, rubber, film, etc).

The thermosetting materials become permanently hard when heated above a critical temperature and will not soften again on reheating (crosslinked). The thermoplastic polymer will soften when heated above its glass transition temperature (T_g) [1] and can be shaped and keeps its shape when cooled. This process is reversible.

A more comprehensive classification divides polymers into:

- Organic polymers
- Semi-organic polymers
- Mineral polymers (inorganic)

Organic polymers consist of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), halogen atoms, and O, N, or S in some cases can be on the backbone chain. Semi-organic polymer chains contain carbon atoms and heteroatoms. For example, poly(dimethyl siloxane), see **Figure 6.4**.

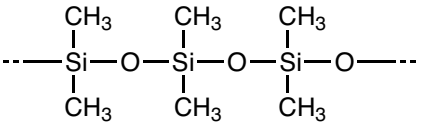


Figure 6.4 Poly(dimethyl siloxane)

Inorganic polymers do not contain carbon atoms, all the elements of group IV can form linear chains analogous to those of polyethylene, see **Figure 6.5**.

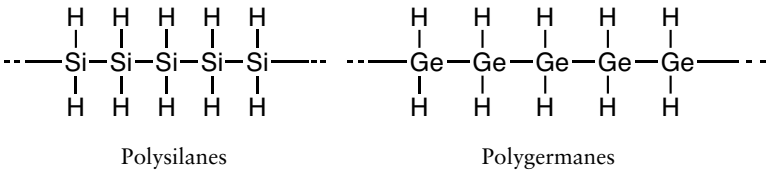


Figure 6.5 Polysilanes and Polygermanes

Polymers may also be classified according to their geometrical shapes:

- Linear (**Figure 6.6**) and branched (**Figure 6.7**) polymers.

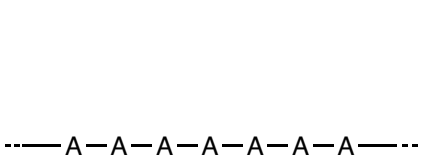


Figure 6.6 Linear Polymer
(A being the mer, the unit of the chain)

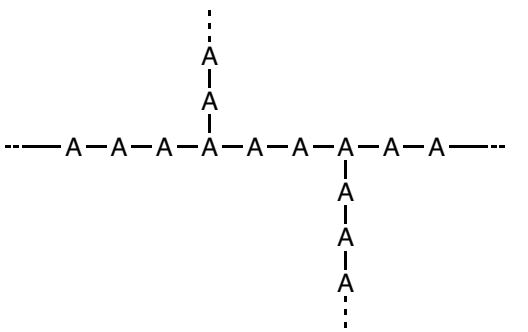


Figure 6.7 Branched Polymer

- Bi-dimensional network (i.e., graphite lattice).
- Three-dimensional network polymers, as shown in **Figure 6.8**.

Figure 6.8 Crosslinked Polymer

6.1.4 Physical Structure

Chain structures of polymers strongly influence the properties of polymers. A three-dimensional arrangement of monomers along the chain is very important and alters the properties of the polymer to a certain extent. The following terms are most commonly used to explain the sequential arrangements of monomers along the chain.

A conformation describes the geometric arrangement of atoms in the polymer chain and configuration denotes the stereochemical arrangement of atoms. Conformation of a polymer chain can be altered by rotation of atoms while configuration of a polymer chain cannot be altered without breaking chemical bonds [2, 5, 7].

Tacticity of a polymer is related to its configuration. If R represents a substituent group, it may have several different placements as it repeats along the chain. In one configuration, all the R groups may lie on the same side of the plane formed by the extended-chain backbone. Such polymers are called isotactic. If the substituent groups regularly alternate from one side of the plane to the other, the polymer is syndiotactic. Polymers with random preferred placement are atactic.

6.1.4.1 Crystalline State

Under suitable conditions, some polymers cooled from the melt can organise into regular crystalline structures and they have less perfect organisation than crystals of low molecular weight substances.

The basic units of crystalline polymer morphology are:

- Lamellae
- Tight or regular loop
- Loose (irregular) loop
- Fringed micelle
- Ringed spherulites, etc.

No polymer is completely crystalline and the chemical structure of a polymer determines whether it will be crystalline or amorphous in the solid state. Tacticity or stereospecificity of the polymer is very important for crystallisation. Atactic poly(vinyl chloride) (PVC) is highly amorphous, while atactic poly(vinyl alcohol) (PVA) is partly crystalline because of the occurrence of specific interchain interactions, (i.e., hydrogen bonding), see **Figure 6.9**.

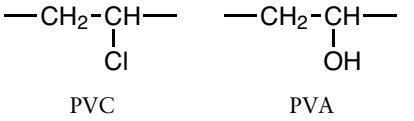


Figure 6.9 Polyvinyl Chloride (PVC) and Polyvinyl Alcohol (PVA)

Isotactic and syndiotactic configurations having specific chain interactions between atoms highly favour the crystal structure.

6.1.5 Morphology Changes in Polymers

No bulk polymer is completely crystalline although single crystals of some polymers such as polyethylene can be grown under laboratory conditions. Polymers can be amorphous or semi-crystalline where regular crystalline units are linked by unoriented, random conformation chains that constitute the amorphous regions. Atactic polymers such as atactic polystyrene, and atactic polymethyl methacrylate (PMMA) are totally amorphous. The presence of a crystalline structure have a significant influence on the physical, thermal and mechanical properties of the polymer. All linear polymers are glasses at sufficiently low temperatures and most long chain, synthetic polymers show a characteristic sequence of changes as they are heated. During heating a certain point is reached at which the amorphous polymer changes from a glass to a rubber. The temperature at which this change occurs is called the glass transition temperature (T_g). If heating is continued, amorphous polymers pass successively through leathery or a retarded,

highly elastic state. A large drop of modulus is observed during this transition. Change in modulus reflects the constant increase in molecular motion as the temperature rises over the T_g. Increasing the temperature further, does not affect the modulus much, but large chain segments undergo conformational rearrangements. This region is called the rubbery state. After the rubbery plateau, decrease in modulus is again observed, this is the rubbery flow region followed by the viscous state. This series of transitions is shown in **Figure 6.10**.

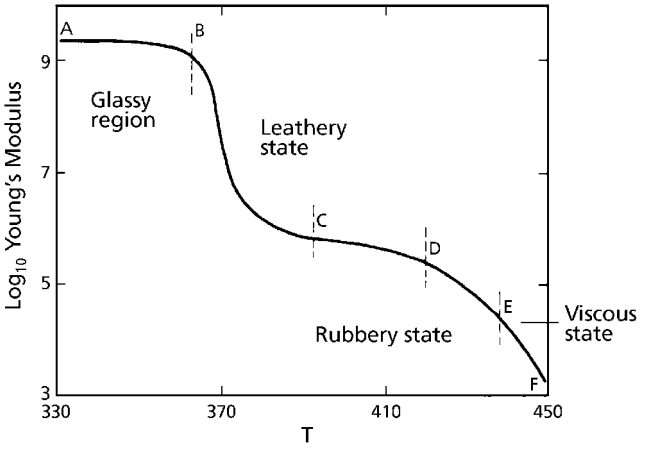
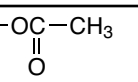
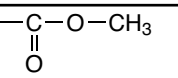
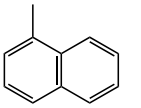
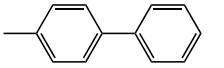
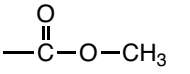
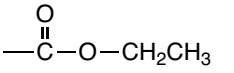
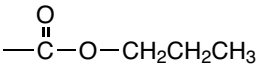
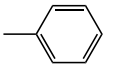


Figure 6.10 Five regions of viscoelasticity, illustrated using a polystyrene sample. The regions between A and B shows glassy, B and C shows leathery C, D, and E shows rubbery, and E and F viscous state.

On the contrary, crystalline polymers remain flexible and thermoplastic above the T_g until the temperature reaches the crystalline melting temperature (T_m). At this temperature, crystalline macromolecular compounds melt to a viscous liquid. Extensive crosslinking may distort the regions and mark the transitions.

As mentioned previously, no polymer is completely crystalline, even the most crystalline polymers such as high density polyethylene have lattice defect regions that contain unordered amorphous material. Therefore, crystalline polymers may exhibit both a T_g corresponding to long range segmental motions in the amorphous regions and a crystalline melting temperature (T_m) at which crystallites are destroyed and an amorphous, disordered melt is formed. When expressed in degrees Kelvin, for many polymers T_g is approximately one-half to two-thirds of T_m.

Table 6.2 Glass transition temperatures for atactic polymers of the general type		
Type of polymer $-(-CH_2CHX-)_n-$	**T_g/K**	**X**
Polyethylene	188	–H
Polypropylene (PP)	253	$-CH_3$
Poly(butyl-1-ene)	249	$-C_2H_5$
Poly(pent-1-ene)	233	$-C_3H_7$
Poly(hex-1-ene)	223	$-C_4H_9$
Poly(4-methyl-1-ene)	302	$-CH_2-CH(CH_3)_2$
Poly(vinyl alcohol)	358	–OH
Poly(vinyl chloride)	354	–Cl
Polyacrylonitrile	378	–CN
Poly(vinyl acetate)	301	
Poly(methyl acrylate)	279	
Poly(ethyl acrylate)	249	$-COOC_2H_5$
Poly(propyl acrylate)	225	$-COOC_3H_7$
Poly(butyl acrylate)	218	$-COOC_4H_9$
Polystyrene	373	
Poly(α-vinylnaphthalene)	408	
Poly(vinyl biphenyl)	418	
Type of polymer $-(-CH_2C(CH_3)X-)_n-$		
Poly(methyl methacrylate)	378	
Poly(ethyl methacrylate)	338	
Poly(propyl methacrylate)	308	
Polymethacrylonitrile	393	–CN
Poly(α-methylstyrene)	445	

6.1.5.1 The Glassy State

Thermodynamically, T_m is a first order transition and T_g is a second order transition. T_g varies with the type of skeletal atoms present, with the type of side groups and even with the spatial disposition of the side groups. As a result, the practical utility of polymers and their different properties depend strongly on their T_g. The transition from a glass to a rubber-like state is accompanied by marked changes in the specific volume, the heat capacity, the refractive index and other physical properties of the polymer. Since it is a second order transition it bears many of the characteristics of a relaxation process and the precise value of T_g can depend on the method used and the rate of the measurement.

Several phenomenological models have been used to provide an understanding of T_g. One of them is an isoviscous state. As a polymer is cooled from its melt state, the viscosity increases rapidly to a common maximum value, approximately 10^{12} Pa-s (10^{13} poise) at T_g for all glassy materials – both low molecular weight and polymeric. Another view is that the T_g represents a state of iso free volume. Free volume, V_f, is defined as the difference between the specific or actual volume V of the polymer at a given temperature and its equilibrium volume at absolute zero Vo, $V_f = V\text{-}V_0$. Each term is temperature dependent [5, 8, 9].

V_f is a measure of the space available for the polymer to undergo rotation and translation, and when the polymer is in the liquid and rubber-like states the amount of free volume will increase with temperature as the molecular motion increases. If the viscous polymer is cooled this free volume will contract and eventually reach a critical value where there is insufficient free space to allow large scale segmental motion to take place. T_g is the temperature at which this critical value is reached. A third view of the T_g is that it represents an isoentropic (same entropy) state.

To transform a polymer into a useful plastic, we have to process it at a temperature higher than T_m or T_g depending on its physical structure, i.e., semi-crystalline or amorphous.

6.1.6 Mechanical Properties

Polymers are used as structural materials, therefore their mechanical properties are very important. Mechanical behaviour of a polymer is its deformation and flow characteristics under stress. The generalised stress-strain curve for plastics is represented in **Figure 6.11**, which serves to define several useful quantities, including modulus or stiffness (the slope of the curve), yield stress, and strength and elongation at break. Polyethylene gives such a curve.

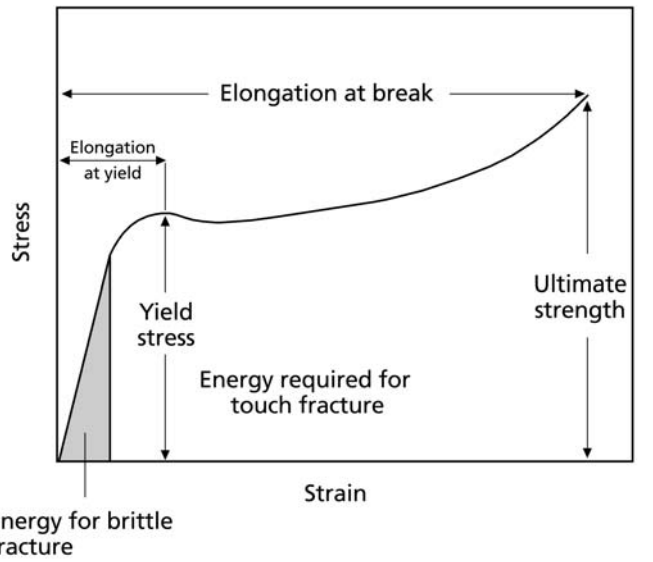


Figure 6.11 Generalised tensile stress-strain curve for plastics

Different types of tests can be performed to measure the following mechanical properties of polymers:

- Tensile strength
- Shear
- Flexure
- Compression
- Torsion

Macro and micro structures of polymers, (i.e., their degree of crystallinity, degree of crosslinking, values of T_g and T_m, the molecular mass and polydispersity), affect the mechanical behaviour of polymers widely. A high degree of crystallinity (or crosslinks) imparts high elastic moduli, low strength and low T_g to macromolecular compounds. The temperature limits of utility of a high polymer are governed by its crystalline Tm and T_g for amorphous polymers; strength is lost above T_g and T_m.

Brittle and tough high polymers like polystyrene and PMMA have high strength and very low extensibility and whereas plastics like polyethylene and plasticised PVC have relatively high extensibility and require much more energy to produce rupture, this energy is represented by the area under the stress-strain curve.

6.1.7 Mechanical Models

A perfectly elastic material obeying Hook's law behaves like a perfect spring, on the other hand, the application of a shear stress to a viscous liquid is relieved by viscous flow, and can be described by Newton's law. Comparison of the two models shows that the spring represents a system storing energy which is recoverable, whereas the dashpot represents the dissipation of energy in the form of heat by a viscous material subjected to a deforming force. Because of their chain like structure, polymers are not perfectly elastic bodies and deformation is accompanied by a complex series of long and short range cooperative molecular rearrangements. As a result, the mechanical behaviour is dominated by viscoelastic phenomena. Creep, stress-relaxation and dynamic response are the result of viscoelastic behaviour of amorphous polymers.

6.1.8 Thermal Properties

Whether undesirable or useful, if a polymer is heated to a sufficiently high temperature, reversible and irreversible changes in its structure will take place. Chain cracking, formation of low molecular weight products (degradation), discoloration and some other changes are mostly not desirable. Yet reversible softening of thermoplastics makes it possible to reshape the material several times. The mechanical properties of thermoplastics are temperature dependent. Thermal expansion and specific heat values of polymers are also very useful for studying the structure-property relation as a function of temperature.

6.1.9 Weathering and Other Properties

Polymers are widely used indoors and outdoors, therefore they are exposed to a chemical environment which may include atmospheric oxygen, acidic fumes, acidic rain, moisture heat and thermal shock, ultra-violet light, high energy radiation, etc. Different polymers are affected differently by these factors even though the amorphous polymers are more sensitive. Ageing is also important and it is defined as the process of deterioration of engineering materials resulting from the combined effects of atmospheric radiation [10], heat, oxygen, water, micro-organisms and other atmospheric factors. Polymer technologists regard it a serious problem to be able to predict the weathering and ageing behaviour of a polymer over a prolonged period of time, often 20 years or more. As a matter of fact, PMMA and other acrylic polymers have outdoor lives of more than 30 years. PVC used in cladding panels for building has a continuous outdoor life of more than 20 years.

From a study done in 1977 on the ageing of about 35 high polymers and organic glasses, it was concluded that ageing occurs in broad temperature ranges below the T_g [10], (i.e., for PVC from +70 to –50 °C and for polycarbonate (PC) from +150 to –100 °C).

Permeability, toxicity, flammability are also some of the important properties of polymers which must be considered during their structural use.

6.2 Additives

6.2.1 Introduction

The properties of polymers may be improved by the presence of appropriately selected additives. Types of additives and their purposes vary and the exact proportions and nature of the additives need some experimentation. Commercial plastics are mixtures of more polymers along with a variety of additives such as plasticisers, thermal stabilisers, flame retardants, processing lubricants and fillers. Specific applications or processing requirements depend on the exact formulation [1, 8].

In some cases, certain properties of a polymer can be enhanced by blending it with another polymer or by copolymerisation with a suitable monomer pair. Additives may be mixed with the polymer before processing by a variety of techniques, such as dry blending, extrusion, compounding, and other methods discussed in Chapter 8.

6.2.2 Classification and Types of Plastics Additives

Classification of additives according to a general scheme is extremely difficult because of the diversity of chemical structures and compositions, molecular weight, natural form, shape, and so on [11]. One way of doing this is according to the original scheme suggested by Mascio [11, 12] in which additives may be classified according to their general and/or specific functions. **Table 6.3**. gives examples of specific groups of additives used with the specified general functions. There are numbers of other kinds of additives which will be discussed when discussing the specific properties of the polymers.

Polymer modification through additives is ultimately related to the affinity of the additive to the matrix which is controlled by physical and chemical interactions. The selection of mixing configuration which in turn, depends on the nature of the additive (low viscosity liquid, low molecular weight solid, melt, liquid) also affects the performance of the additive. Additives forming distinct dispersed morphologies may be deformable or rigid

Table 6.3 Examples of specific groups of additives	
Additives Which Modify Mechanical Properties	
Plasticisers	Phthalate, trialkylphosphate, adipate esters Chlorinated paraffins High molecular weight polyesters Epoxy derivatives
Impact modifiers	EPR, EPDM NBR, NR, various elastomers EVA, MBS, CPE
Crosslinking agents	Organic peroxides, coagents, rubber curatives
Additives Which Modify Electrical Properties and Flame Retardancy	
Flame retardants and smoke suppressants	Sb_2O_3, MoO_3, molybdate salts, zinc borate Chlorinated paraffins, brominated organic compounds Organophosphate esters $Al(OH)_3$, $Mg(OH)_2$
Conductive additives	Carbon black, carbon/graphite fibres, metals, metallised fibres/reinforcements
Processing Additives	
Stabilisers	Primary antioxidants (sterically hindered phenols, secondary aryl amines) Hydroperoxide decomposers (organophosphites, thioesters) Acid absorbers (lead salts, Ca/Ba-Ba/Cd-Ba/Sn salts, organotins, epoxidised oils)
Lubricants	High molecular weight fatty acids and derivatives Paraffin, ester and amide waxes Metal soaps Silicones, polyfluorocarbons
Flow and fusion promotor	PMMA and acrylate ester copolymers, MBS
Anti-ageing Additives	
Anti-oxidants	Sterically hindered phenols Secondary-aromatic amines Phosphites, thioesters

Table 6.3 Examples of specific groups of additives (*continued*)	
Anti-ageing Additives *Continued*	
Metal deactivators	Chelating agents (hydrazones, oxamides, hydrazides, phosphites, phosphines)
Light stabilisers	Pigments (carbon black, iron oxides) UV absorbers (hydroxyphenones, benzotriazoles) Excited state quenchers (organic Ni complexes) Free-radical scavengers (piperidines, HALS)
Optical Property Modifiers and Blowing Agents	
Pigments	Inorganic: Ti, Fe, and Cr oxides, Cd, Ba and Pb sulfides, sulfates, and chromates. Organic: carbon black, quinacridones, azo pigments
Dyes	Anthraquinones Azo and bisazo compounds Nigrosines
Nucleating agents	SiO_2, talc, sodium benzoate
Blowing agents	Inert gases (CO_2, N_2) Hydrocarbons, halocarbons Chemical blowing agents (azodicarbonamide), bicarbonates
Surface Modifiers	
Antistat(ic)s	Ethoxylated amines and quaternary amonium salts Phosphate ester Glycerides
Antiblocking agents, slip additives	Amide waxes, oleamide
Antifoggers	Polyethers
Antiwear additive	Polytetrafluoroethylene (PTFE)
Wetting agents	Ionic, nonionic surfactants
Adhesion promotors	Silanes, titanates Block and graft copolymers*
**Particularly important for immiscible polymer blends (compatibilisers, coupling agents, interfacial agents).*	
CPE: Chlorinated polyethylene EPDM: Ethylene propylene diene monomer EPR: Ethylene propylene rubber EVA: Ethylene vinyl acetate	HALS: Hindered amine light stabiliser MBS: Methacrylate butadiene styrene NBR: Acrylonitrile butadiene rubber NR: Natural rubber

[11-15]. Whether deformable or rigid, important characteristics controlling the degree of dispersion, resulting morphology and the final properties are:

- Viscosity and elasticity at processing conditions
- Concentration
- Interfacial tension
- Particle size and shape, size distribution, surface area and volume fraction
- Bulk properties, surface tension and surface reactive sites.

6.2.2.1 Plasticisers

A plasticiser is a material incorporated in a plastic to increase its workability and flexibility or distensibility. The melt viscosity, elastic modulus and T_g of a plastic are lowered by a plasticiser addition. There are several theories to explain plasticiser effects such as the lubricity, gel, and free volume. Plasticisers are essentially nonvolatile solvents and therefore, polymer and plasticiser compatibility is very important and the solubility parameter difference ($\Delta\delta$) should be less than 1.8. When present in small amounts plasticisers generally act as antiplasticisers, (i.e., they increase the hardness and decrease the elongation of polymers). **Figure 6.12** illustrates the effect of plasticiser on modulus. Increasing concentration of the plasticiser shifts the transition from the high modulus (glassy) plateau region to the low, i.e., to occur at lower temperature [9].

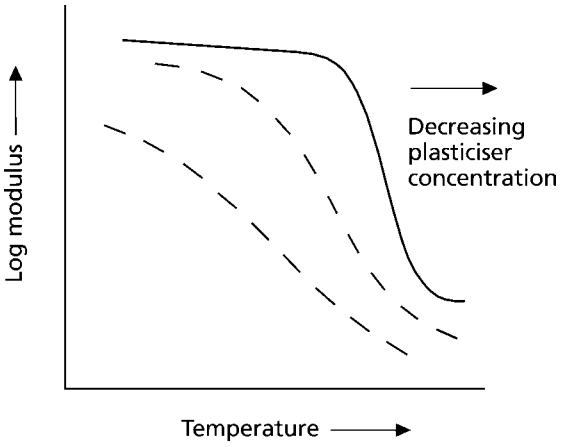


Figure 6.12 Effect of increasing plasticiser concentration on the modulus-temperature plot

A very useful equation relating T_g to the composition of a polymer mixture from known parameters is given as:

$$\ln \frac{T_g}{T_{g,1}} = \frac{w_2 \ln(T_{g,2}/T_{g,1})}{w_1(T_{g,2}/T_{g,1}) + w_2} \tag{6.9}$$

In the equation, T_g is the glass transition temperature of the mixture, $T_{g,1}$, $T_{g,2}$ are the glass transition temperatures of components 1 and 2, and w_1, w_2 are the weight fractions of components 1 and 2, respectively.

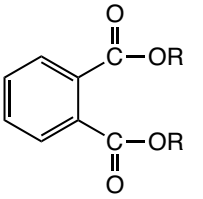
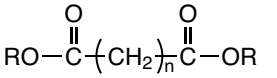
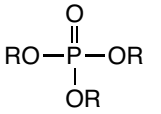
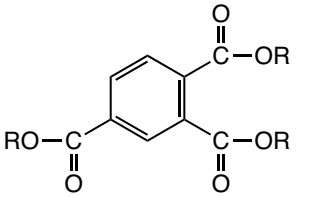
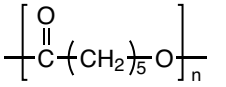
Table 6.4 shows some common plasticisers for PVC. The actual reduction in polymer T_g per unit weight of plasticiser is called the plasticiser efficiency.

Plasticisation may occur either internally or externally. In some cases, plasticiser function can be obtained by copolymerising the polymer with the monomer of a low T_g polymer such as PVA, this process is called internal plasticisation, typical external plasticisation is addition of dioctyl phthalate, diisooctyl phthalate and di-2 ethyl hexyl phthalate to PVC.

Water is a widely utilised plasticiser in nature which permits flexibility. Most plastic floor tiles become brittle with extended use, mainly due to the leaching out of the plasticiser. This may be overcome through many routes including surface treatment of polymer product surface, effecting less porous surface features and, use of branched polymers which can act as plasticisers to themselves.

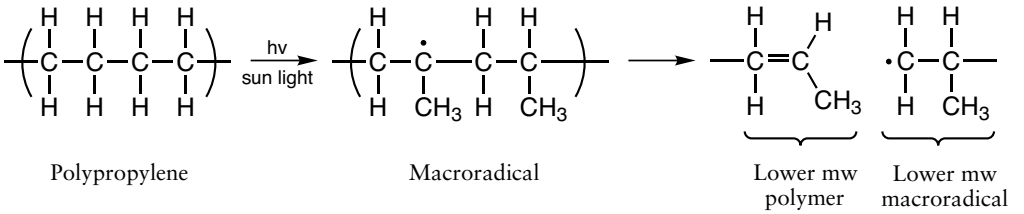
6.2.2.2 Fillers and Reinforcements

Fillers are inert materials and important additives for thermoplastics and thermosets. They reduce the resin cost and improve processibility or dissipate heat in exothermic thermosetting reactions. Some examples of fillers include wood flour, clay, talc, fly ash, sand, mica and glass beads. Graphite, carbon black, aluminum flakes and metal and metal coated fibres are used to minimise electrostatic charging. Reinforcing fillers are used to improve some mechanical properties such as modulus, tensile or tear strength, abrasion resistance and fatigue strength. Carbon black, silica, woven fabrics and chopped fibres are used for this purpose.

Table 6.4 Common plasticisers for PVC		
Plasticiser class	**Chemical structure**	**Examples**
Dialkyl phthalate		DOP, DIOP
Aliphatic diester		DOA
Trialkyl phosphate		TCP
Trialkyl trimellitate		TOTM
Polycaprolactone		
DOP: dioctyl phthalate DIOP: diisooctyl phthalate DOA: dioctyl adipate TCP: tricresyl phosphate TOTM: trioctyl trimellitate		

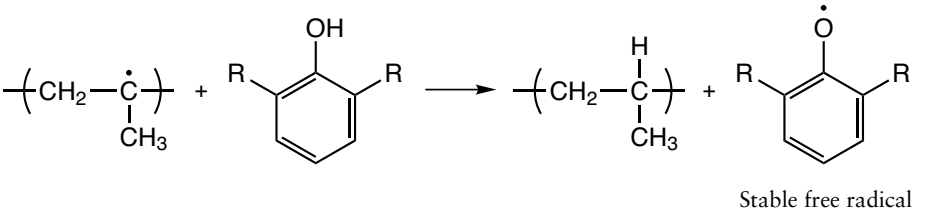
6.2.2.3 Antioxidants

Some polymers are not too stable outdoors due to their molecular structure like polypropylene, which has a readily removable hydrogen atom on the tertiary carbon atoms. In the absence of stabilisers, chain degradation may take place, see **Reaction 6.10**.



Reaction 6.10

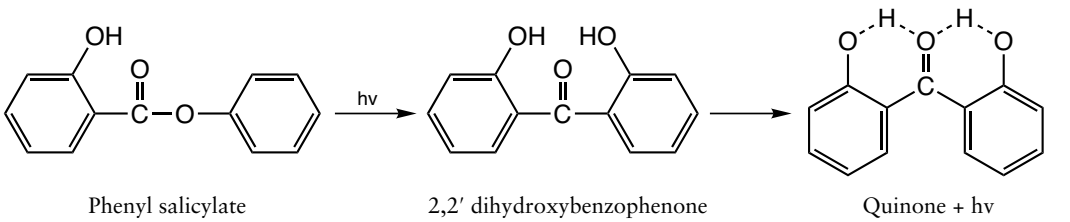
Chain reaction degradation is retarded by the presence of small amounts of antioxidants which are derivatives of phenols or hindered phenols, alkyl phosphites or thioesters and carbon black [8], see **Reaction 6.11.**



Reaction 6.11

6.2.2.4 Ultraviolet and Light Stabilisers

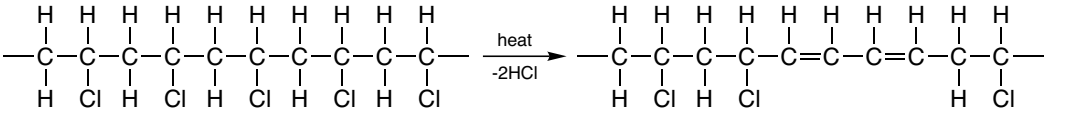
Radiation stabilisers absorb radiation prior to molecular bond breakage. The high energy radiation of sun that reaches the earth's surface is sufficiently strong to cleave covalent bonds and cause yellowing and embrittlement of organic polymers. Phenyl salicylate rearranges in the presence of high energy radiation to form 2,2′ dihydroxybenzophenone, so it acts as an energy-transfer agent, see **Reaction 6.12.**



Reaction 6.12

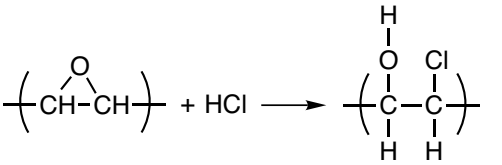
6.2.2.5 Heat Stabilisers

Another type of degradation (dehydrohalogenation) also occurs with chlorine containing polymers such as PVC. PVC may lose hydrogen chloride when heated and form a chromophoric conjugated polyene structure. Since the allylic chlorides produced are very unstable, the degradation continues as an unzipping type of chain reaction, see **Reaction 6.13**.



Reaction 6.13

This type of degradation is accelerated in the presence of iron salts, oxygen and hydrogen chloride. There are some HCl scavengers, some of which are toxic and some are less toxic such as mixtures of magnesium and calcium stearates, and dioctyl tin salts. Less toxic, epoxidised, unsaturated oils such as soy bean oil also act as an HCl scavenger as shown in **Reaction 6.14**.



Reaction 6.14

6.2.2.6 Flame Retardants

Many flame retardants are halogen or phosphorus compounds. These may be:

(a) additives,

(b) external retardants such as antimony oxide and organic bromides,

(c) internal retardants, such as tetrabromophthalic anhydride which can become part of the polymer. A compound which is not a good fuel may have flame retardant properties

such as polyfluorocarbons, phosphazenes and some composites. Fillers such as alumina trihydrate release water when heated and hence reduce the temperature of the combustion reaction. Char, formed in some combustion process, also shields the reactants from oxygen and retards the outward diffusion of volatile combustible products. Aromatic polymers tend to char, and some phosphorous and boron compounds catalyse char formation. Antimony trioxide and an organic bromo compound are more effective than single flame retardants because of their synergistic flame retardant properties [8, 9, 11].

6.2.2.7 Curing Agents

Curing is applying heat (and pressure) to change the properties of rubber or thermosetting resins. Vulcanisation of *Hevea* rubber with sulfur by Charles Goodyear in 1938 is an old example of a curing process. Then, in the 1900s, hexamethylene tetraamine was used as a curing agent (crosslinking agent) for A- or B-stage novolacs.

The curing of polyesters, ethylene-propylene copolymers, and for the grafting of styrene onto elastomeric polymer chains, benzoylperoxide is used. High density polyethylene (HDPE) is crosslinked in the presence of 2,5-dimethyl-2,5-di(*t*-butylperoxy)hexyn-3. Crosslinking is achieved by electrons, γ-rays or UV irradiation, and enhanced by the presence of methyl ether of benzoin.

6.2.2.8 Processing Additives

Lubricants are processing additives, which improve flow during processing by reducing melt viscosity (internal lubricants) or by reducing adhesion between methalic surfaces of the processing equipment and the polymer melt (external lubricants). Important lubricants are: amides, esters, metallic stearates (often used for PVC), waxes, acids, mineral oils, and low molecular weight polyolefins.

6.2.2.9 Blowing Agents

Many plastics such as polystyrene (PS), expanded polystyrene and polyurethanes are foamed to provide insulating properties (rigid foam) or flexible properties (flexible foam) for seat cushions and other applications. Blowing and foaming agents are used for this purpose and examples of physical blowing agents are volatile liquids such as short chain hydrocarbons, (e.g., pentanes, hexanes, heptanes) and fluorocarbons, (e.g., trichloromethane, tetrachloromethane and trichlorofluoromethane), and gases such as

nitrogen, carbon dioxide and air. In the case of polyurethanes, flexible foams are produced by the production of carbon dioxide from the reaction of an isocyanate and water [9].

6.3 Structure-Property Relationships

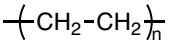
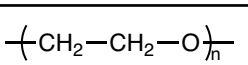
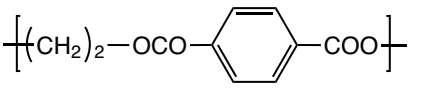
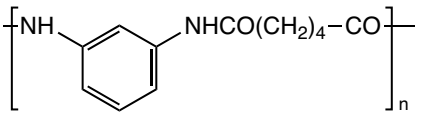
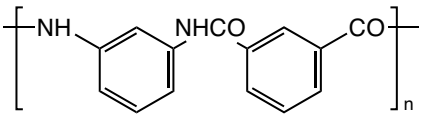
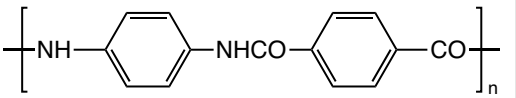
A fundamental knowledge of structure-property relationships is required as the demand for the use of synthetic polymers to replace or supplement more traditional materials such as wood, metals ceramics and natural fibres is increasing and has stimulated the search for even more versatile polymeric structures covering a wide range of properties. After establishing the suitability of a polymer for a particular purpose, i.e., whether it is glass-like, rubber-like or fibre forming, one has to consider the characteristics dependent primarily on chain flexibility, chain symmetry, intermolecular attractions and of course environmental conditions. These properties, excluding environmental, are reflected in values for T_m, T_g, modulus and crystallinity [8].

6.3.1 Control of T_m and T_g

As discussed in section 6.1, chain symmetry, flexibility and tacticity can influence the individual values of both T_m and T_g. As discussed earlier a highly flexible chain has a low T_g which increases as the rigidity of the chain becomes greater. Also, strong intermolecular forces tend to increase T_g and increase crystallinity. **Table 6.5** shows the effect of aromatic rings on chain stiffness on T_g and T_m. In the polyamide and polyurethane series hydrogen bonding strengthens the crystallite regions and increases T_m. The effect is strongest when regular evenly spaced groups exist in the chain. An alternative method of reducing the hydrogen bonding potential and hence T_m, in the polyamides is to increase the length of the $(CH_2\text{-}CH_2)_n$ sequence between each bonding site [5].

6.3.2 Effect of Macromolecular Skeleton

The environment in which the macromolecule finds itself is important in discussing structure-property relationships. The environment is solvent molecules when the macromolecule is in solution, it is the other polymer molecules in solid state, and at the surface, the vapour or the liquid that are in contact with the surface. The skeleton of the polymer where the flexibility and stability are highly affected and the types of side groups are important in discussing the structure property relationships. The carbon-carbon single bond confirms appreciable flexibility to a polymer chain but, its weakness is its sensitivity to thermooxidative cleavage. The aliphatic carbon-carbon double bond

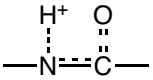
Table 6.5 Effect of aromatic rings on chain stiffness, as shown by the values of T_m and T_g		
Structure	**T_g/K**	**T_m/K**
	188	400
	206	339
	-	About 653
	342	538
	320	538
	-	613
	546	About 635 (decomposition)
	-	About 773

has a barrier to internal rotation which generates chain stiffness and high T_g. However, when the double bonds are alternating, skeletal rigidity is generated along with colour and electrical conductivity.

Aromatic rings in a polymer skeleton confer rigidity and extended chain character and in aromatic polyamides, polyesters or polyarylenes can also show main chain liquid crystallinity. In **Table 6.5**, a few examples with their T_g and T_m values are given.

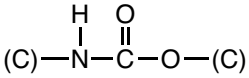
Oxygen atoms in a hydrocarbon chain give torsional mobility and materials flexibility. Nearby skeletal units have to be taken into consideration as ether linkages are generally stable to hydrolysis and to thermooxidation while polyaldehydes depolymerise readily at moderate temperatures.

The amide linkage makes the chain stiffer because of the partial double bond character of the N-C bond which causes a possibility for internal and external hydrogen bonding:



Many commercial polyamides are highly crystalline and have repeating units within each crystalline region are inaccessible to water or other reagents.

Urethane linkages:



in polymers should give hydrolytically sensitive sites to the chain and are considered to be a source of molecular flexibility, and this property enables the use of many polyurethanes as elastomers.

The silicone-oxygen bond has one of the highest torsional mobilities in any polymer backbone, e.g., T_g of poly(methyl siloxane) is –130 °C. Polydimethylsiloxane (-$[Si(CH_3)_2O]_n$-) is more stable to thermooxidative attack than is the aliphatic C–O bond but is sensitive to certain reagents such as acids and bases.

Even though a double bond, –P=N–, is present in the structure of a phosphazene linkage it gives very high flexibility to the polymer chain. The phosphorus-nitrogen skeleton has a high chemical, photolytic and thermo oxidative stability and appears to be resistant to ozone and a variety of free radical reagents. Also, nitrogen atoms in the phosphazene groups can complex to metal ions.

6.3.3 Effect of Different Side Groups

The side groups attached to a polymer chain can have a more profound effect on the polymer properties than the skeleton itself. Side groups are responsible for several properties such as protecting the skeleton against chain cleavage reactions, solubility properties, steric and polar interactions between side groups on the same chain or different chains which determine the T_g, crystallinity and surface properties of the material.

Among the alkyl side groups, methyl side groups are present in many polymers, as shown in **Figure 6.13**:

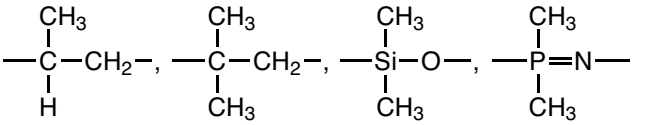


Figure 6.13 Polypropylene, polyisobutylene, polydimethyl siloxane

They enhance the hydrocarbon character of the skeleton, making them hydrophobic and soluble in organic solvents. In polypropylene, the methyl group determines the tacticity of the polymer – and as a result, isotactic polypropylene is a crystalline thermoplastic. Ethyl-, propyl-, butyl-, or higher alkyl side chains generally increase the hydrocarbon character and the confirmational disorder introduced by these side groups may prevent crystallisation yet, longer chain side units undergo crystallisation.

Aryl side groups are hydrophobic and relatively bulky. They impose stiffness and steric hindrance to the main chain as in polystyrene and increase T_g. Aryl side groups are not only phenyl rings but they may appear as mesogenic side groups as well. Biphenyl, aromatic azo, or cholesteryl units in a side group may generate side chain liquid crystallinity, see **Figure 6.14**.

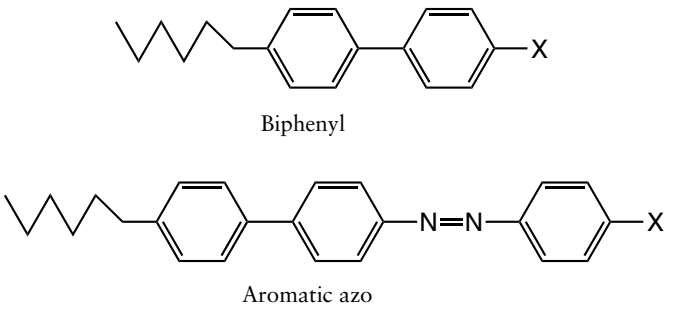


Figure 6.14 Biphenyl and aromatic azo units

It is also possible to have halogen side groups, such as fluorine and chlorine. Polymers with fluorine in their side groups have extreme hydrophobicity and water insolubility. This raises the thermal and oxidative stability and confers solvent, fuel and oil resistance. Some examples of fluoro polymers are poly(tetrafluoroethylene) (Teflon),

poly(vinylidene fluoride) (PVDF) – a variety of fluoro chloro carbon elastomers, fluoro alkyl siloxane elastomers, and fluoro alkyl oxy phosphazene elastomers. Chlorine side groups polymers are relatively resistant to chemical attack. PVC and poly(vinylidene chloride) are stable polymers that are widely used. One or more chlorine atoms per repeat unit, connected directly to a carbon skeleton increase chain stiffness. Carbon-chlorine bonds are not stable to sunlight. Cyano side groups also impose a special set of properties on the carbon backbone polymers, e.g., acrylonitrile, -CHCN-CH_2-, such as reducing solubility in nonpolar solvent and increasing it in dimethylformamide, dimethylsulfoxide or dimethylacetamide. Copolymers of acrylonitrile are used in solvent- and oil-resistant elastomers. The T_g of polyacrylonitrile is 85 °C.

Hydroxyl groups in polymer chains impart hydrophilicity and water-solubility to the polymer. They form strong hydrogen bonds which increase the T_g of the polymers. Ester side group polymers can be polyacrylic acid esters, polymethacrylic acid esters, or esters of poly(vinyl acetate) (PVAc), see **Figure 6.15**.

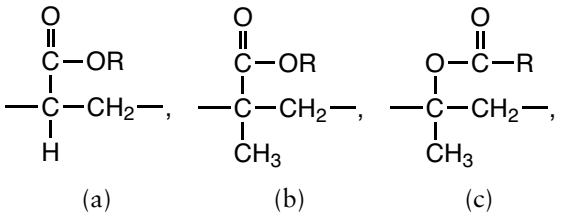


Figure 6.15 (a) polyacrylic esters; (b) polymethacrylate acid esters; (c) polyvinyl acetate esters

The T_g of carbon backbone polymers with ester side groups vary widely with the tacticity and the nature of the R groups. Atactic PMMA has a T_g of 105 °C while PVAc has a T_g of 28-31 °C. They are all nontoxic [6].

6.3.4 Some Structure-Property Relations of Polymers as Regards Building and Construction

Plastics materials will not reduce the demand for bricks, mortar and concrete but it is clear that as the construction industry gains confidence in using new materials, their influence is likely to spread. The main uses of plastics materials and their applications in building construction can be summarised as in **Table 6.6**.

Table 6.6 Typical plastics materials used in building and construction	
Applications	**Polymeric material(s)**
Windows and glazing	Acrylics, PC, PVC, PS (internal)
Roof lights and insulated roof glazing	Acrylics, GRP, PC, PVC
Roofing	PVC, PVC (wire), GRP, PC, PVDF, PVDC, (also butyl- EPDM and CSM rubbers)
Suspended ceilings	Acrylic, GRP, PS, PC
Walls and partitions	GRP, PP, PVC, PVC/acrylic, PVC/PC
External cladding	GRP, PVC, ABS/acrylic/PVDF
Insulation	PUR, PIR, phenolic, furane, PS, UF
Cable, wiring	PVC, polyethylenes
Pipes	PVC, polyethylenes, ABS, PP polybutylene, GRP
Flooring	PVC, epoxy
GRP: Glass reinforced plastic PVDC: Poly(vinylidene chloride) CSM: Chlorosulfonated polyethylene ABS: Acrylonitrile butadiene styrene PUR: Polyurethane PIR: Polyisocyanurate UF: Urea formaldehyde	

6.3.4.1 Poly(Vinyl Chloride) (PVC)

PVC is used in the construction sector in:

- Pipes and fittings
- Cladding and profiles
- Wall coverings
- Floor covering
- Film/sheet

Lead, barium and cadmium based stabilisers are widely used for rigid PVC [16]. However, calcium and zinc containing materials are preferable as they offer good heat and weather stability and are used in flexible PVC applications. Foamed PVC can be considered more

as a wood substitute than the traditional PVC profiles. It is suitable for both interior and exterior applications and unlike wood it does not need any special treatment.

Research in PVC is continued with great enthusiasm by many scientists. In the study of Stoeva and co-workers [17] the effect of a natural, activated and modified microzeolites are studied individually and in combination with ammonium sulfamate as high-melting dispersed additives. Their effect on the mechanical properties and as a fire retardant additive are also discussed. It is reported that the strength-deformation properties of PVC are improved within the interval of 3-8 wt% of additive.

6.3.4.2 Polyethylene (PE) and its Copolymers

Polyethylene owes its success in pressure piping to a number of factors, mainly to its flexibility and resulting properties are long coil length, fewer joints, quicker installation, low sensitivity to earth movements and good potential for relining. Being noncorrosive results in long, maintenance-free service [5, 16]. Production of pipes in large diameters for high pressures can lead to wall thickness problems. The new HDPE materials which show bimodal molar mass distribution solved this problem. Based on bimodal polymerisation technology with highly active Ziegler catalysts, the comonomer can be incorporated into the higher molecular mass fraction and so be dispersed throughout the structure. The 'tie molecules' connect the crystallite lamellae and are responsible for enhanced mechanical properties, high resistance to crack growth, high creep resistance, ductile failure only at high stress and no brittle fracture by chain rupture.

Olefinic polymers are transparent at normal room temperatures but become milky when exposed to bright sunlight and they are designed to provide shade and prevent overheating from incident solar radiation. Light hitting the polymer is scattered, thus reducing heat build up, but still allowing brightness, within rooms. The scattering centres arise when the polymer mixtures become incompatible with each other. This is overcome by varying the polymer structures to produce a substance, which is miscible at low temperature. A polymer blend is intended for film or sheet extrusion in applications to cover skylights, greenhouse and conservatory panels. Hydrogel formation is also possible with PE.

Bouma and co-workers studied the foam stability related to low density polyethylene using low molecular weight additives such as alkanes (isobutane) as blowing agents and stearyl stearamide as an additive [18]. The results of this work indicate that phase separation occurs, resulting in migration of the low molecular weight additive to the surface. Formation of a more or less structured layer of the additive at the surface explained the low isobutane permeability.

6.3.4.3 Styrenics

The use of PS as expanded PS (EPS) foam gained much importance in civil engineering due to its good insulating value, excellent moisture resistance, predictable long-term performance under real-life conditions, stable and low conductivity value, mildew/corrosion resistance, compressive strength, toughness and durability. Most PS is used as expanded blocks or extruded foam sheet for insulation purposes.

ABS terpolymer is used as a window profile material which is co-extruded with a weather protection layer. Impact strength and dimensional stability are claimed to be greater than for PVC.

Interesting research on the dynamic mechanical and thermal properties of fire-retardant high-impact polystyrene (HIPS) is published by Chang and co-workers [19]. HIPS may be produced by the free-radical chain polymerisation of styrene in the presence of an unsaturated elastomer. The authors showed that the melting point of the additive in relation to the processing temperature of the thermoplastics and the compatibility of the additive with the polymer phases are the two important variables governing the interaction of additive with polymer matrix.

6.3.4.4 Acrylics

PMMA sheets with an added elastomer component offer optical clarity and are resistant to crazing impacts, ageing and weathering. Acrylic sheets are the top surface layer of baths and other bathroom wares.

6.3.4.5 Engineering Thermoplastics

Among the several engineering thermoplastics some interesting research on amine cured epoxy resins [20, 21] and bisphenol A polycarbonate [22] will be discussed next. The reaction product of 4-hydroxyacetanilide and 1,2-epoxy-3-phenoxopropane, when added at 19 wt% to a conventional epoxy-resin curing agent mixture, increases the tensile strength of the cured system from 82 MPa to 123 MPa and increases the shear modulus from 970 MPa to 1560 MPa, but this system fails with appreciable localised deformation occurring during fracture. The other study on the structure-property relationships as a tool for the formation of high performance epoxy-amine networks [19], chose an additive miscible in the mixture of monomers, but which gives rise to phase nano-separation along the network construction. The study on the effect of ionic additives on the deformation behaviour of bisphenol A PC [22] reflects that the

impact strength of PC markedly decreased as the content of additive increased and brittle fracture of PC was observed in tensile tests when the concentration of additive was above 2.5 phr, while critical shear yield stress and critical craze stress appeared to exist in the range of 2.5 to 3.5 phr of additive.

6.3.4.6 Polyurethanes (PU)

PU is manufactured by the condensation polymerisation of polyol (from crude oil) and isocyanate. In civil engineering, PU block foams and the continuous laminated foams are used for various applications such as roofing or sealing strips, glass fleece, metal or plastic foils, all used as facing [17]. Rigid PU foam has physical stability and excellent thermal insulation qualities and is used extensively in the walls and roofs of buildings where a very high standard of insulation is required. When heated PU decomposes in the temperature range of 400-500 °C, it is less toxic than wood and cork decomposition. In the case of fire, the thermoset PU rigid foam does not melt and does not form burning droplets.

In the manufacture of flexible foams, carbon dioxide generated from the water-isocyanate reaction has replaced the external blowing agent, yet methylene chloride is still widely used with acetone and liquid carbon dioxide. Cyclopentane has become the main blowing agent for refrigeration appliances, *n*-pentane has only been exploited for sandwich panels and other building insulation.

Use of water-dispersible or water-soluble polyether-urethanes, which optionally contain isocyanate groups as additives for inorganic binders in the preparation of building materials, particularly a high-density or high strength mortar or concrete composition has been studied by Laas and co-workers [23]. The building material results from the use of the water-dispersible or water-soluble polyether-urethanes.

6.3.4.7 Bitumen Modification

Styrenics have a significant use as modifiers for asphalts and bitumens. They improve the flexibility of the base materials, especially at low temperatures and they also reduce the tendency to flow at higher temperatures. Additionally, they are also effective in improving the softening point, stiffness, ductility, tensile strength and elastic recovery [6]. Generally less than 20% of the thermoplastic elastomer is added to the blend, even 3% can make a significant difference to the properties. Applications include road surface dressings such as chip seals, road crack seals, slurry seals, asphalt concrete, roofing and waterproofing.

Styrene-butadiene-styrene (S-B-S) block copolymers are used in bitumen roofing formulations because of their suitable dynamic viscoelastic properties.

A study on the bitumen-free binder, especially for building materials such as surfacing for traffic areas, sports grounds, etc., used in sealing compounds, jointing compounds, insulating paints and surface coating is characterised by Sychra and Steindl [24].

It consists essentially of an oil modified with 0.1 to 40 pbw, preferably 1 to 10 pbw of sulfur. A building material mixture can include, along with the bitumen-free binder, up to 98 pbw of inorganic additives. The bitumen-free binder can also be used in the form of an aqueous dispersion as insulating paint or surface coating.

6.3.4.8 Polymer Modification of Asphalt

S-B-S rubber polymer (11-15 weight%) or polypropylene (25-30 weight%) based on asphalt is used in roofing. These higher loadings lead to polymer network formation wherein the polymer becomes the continuous phase and the asphalt becomes the discontinuous phase. Modification of asphalt by mixing with PP or S-B-S is favoured economically. Star-shaped S-B-S will provide high viscosity, high softening point and better low temperature flexibility to the compound. Linear S-B-S will impart low viscosity, low softening point and better toughness. To provide strength and reduce cost, S-B-S as well as PP modified asphalts are filled with fillers, e.g., calcium carbonate and clays.

Fibrillated PTFE and molybdenum disulfide particles are other bitumen and asphalt modifiers. The copolymer comprises two incompatible polymers forming a two-phase copolymer including a thermoplastic and block polymer and an elastomeric mid-block polymer. The asphalt modifier is made by mixing together, under high shear, particles of thermoplastic elastomeric copolymer, and molybdenum disulfide until the PTFE is fibrillated and combined with the thermoplastic elastomer.

6.4 Polymer Composites

6.4.1 Introduction, Definitions and Classifications

Structural materials can be classified as metals, ceramics or polymers, each with its own advantages and disadvantages. For example, metals are strong, tough, inexpensive, but are heavy, chemically reactive and limited to service temperatures below 1,000 °C. Ceramics are hard, chemically stable and useful at high temperatures, but they are brittle and difficult to fabricate. Polymers are light, easy to process, but are relatively

weak and they are limited to lower service temperatures below 300 °C. Composites are the combination of two or more of these materials combined together which offer an excellent balance of properties in one material, by eliminating undesirable properties and retaining the desirable ones of the components. 'Composite' is an anisotropic material with two or more components differing in form or composition on a macroscale, having two or more distinct phases with recognisable interfaces between them [25, 26]. Polymer composites usually consist of a reinforcing material (constituting the first component and phase), embedded in a polymer matrix (called the binder, which is the second component and continuous phase). Since one of the main objectives in any structural design is to minimise weight, low densities are important, as well as high strengths and moduli, all of which can be provided by composite structures with economic viabilities.

In general, various material properties of composites, are optimised and are better than those of the individual constituents, as a result of the principle of combined action. Frequently, composites offer an excellent opportunity to eliminate some of the undesirable properties while retaining the desirable properties of the constituents. Hence, one can produce a material with better mechanical properties (mainly strength), improved chemical and/or physical properties (such as smaller thermal expansion/and better thermal conduction values, improved specific heats, higher softening and melting points, improved electrical conductivities/electrical permittivities, dielectric loss, improved optical and acoustical properties) by shifting to a composite material. In most of these, structural weight savings while retaining the reliability and strength are achieved together by using composite materials [27]. There are three main factors that may affect the competition between composites and traditional engineering materials with similar mechanical properties: the cost, the reliability and the degree of complexity involved. The cost barrier for composites is usually overcome by the mass production and the reliability is achieved successfully as explained. However, the degree of complexity is certainly more critical for composites which is due to the unisotropy existing (at least on microscale) for these structures. It is known that, in composites, thermoelastic properties as well as strength and failure modes have strong directional dependencies, which may be the only disadvantage of using these materials.

There are already a number of composite materials of natural origin known, i.e., bone is one of them and wood is the other. Also, crushed rock aggregate commonly used in concrete in civil engineering, is a typical composite structure which improves the compressive strength of the matrix appreciably. During the last few decades, there has been an ever increasing demand for materials that are stiffer and stronger, yet lighter, in various structural, aeronautical, energy and civil engineering applications, but so far there is no monolithic engineering material available to satisfy all, which certainly led to the concept of combining and using different materials in a composite structure.

6.4.1.1 Matrix Related Classification of Composites

In composites, the matrix can be either polymeric, ceramic or metallic, hence, polymer matrix composites (PMC), ceramic matrix composites (CMC) or metal matrix composites (MMC). Obviously, the latter two structures are used for high temperature applications (>315 °C), where PMC are usually inadequate. In addition, MMC with proper electrical and thermal conductivities are also used in heat dissipation/electronic transmission applications. In addition to the general types of composites, some specific composites can also be of the type ceramic/metal/polymer or carbon matrix (CMC) or even hybrid composites (HC).

In this chapter, only PMC that are used in construction will be covered in any detail.

In general, the following principle is used in the incorporation of dispersed phase into the matrix, in the production of a composite: the matrices selected for use are of lower modulus, while the dispersed reinforcing elements are typically some 50 times stronger and 20-150 times stiffer. One should note, that the properties of the matrix are particularly important in most polymer composite systems - as in such systems, the matrix bears the load and it is distributed between the matrix and reinforcing particles. Each matrix type with different incorporated phases certainly has a different impact on the processing technique to be used.

By embedding natural and near-natural reinforcing fibres (such as flax, cellulose) into a biopolymeric matrix (from cellulose, starch or lactic acid derivatives, thermoplastics as well as thermosets), a new group of fibre reinforced systems are also created, called as 'biocomposites' [28].

More in-depth information about the polymer matrices is given in Section 6.2.2.

6.4.1.2 Dispersed Phase Related Classifications of Composites

Dispersed (or reinforcing) phase in composites usually exists with substantial volume fractions (10% or more). The most commonly used reinforcing component is either a particulate or a fibrous form (continuous/discontinuous chopped fibre), hence the following three common types of composites can be produced, depending on the size and/or aspect ratio and volume fraction(s) of reinforcing phase(s):

(a) particle strengthened,

(b) discontinuous (chopped) fibre reinforced,

(c) continuous fibre reinforced composites.

Within these, fibre reinforced composites (FRC) are the most commonly used in structural applications where the reinforcing component is of utmost importance: fibres bear the main load and the function of the matrix is confined mainly to the load distribution and its transfer to the fibres.

Feldman [1] used a different terminology - if all the dispersed phases are between 10-1000 nm in size with only one continuous phase they are called microcomposites, and if there is more than one continuous phase present they are macrocomposites. In addition, if the sizes of the reinforcing components in a microcomposite are in the form of 'quantum dots' specifically smaller than 25 nm, a nanocomposite is obtained. The term flexible composite is used to identify composites based on elastomeric polymers where the usable range of deformation is much larger than conventional thermoplastic or thermosetting composites [29].

There are also cases where reinforcing phases are in the form of sheets bonded together and they are often impregnated with more than one continuous phase in the system [27], which are known as laminar composites (or simply laminates). Sandwiching a lightweight polymeric core material (which can be a foam of a thermoplastic or a thermosetting plastic or even a honeycomb web of a nonmetallic, such as aramid or carbon) between the skins of a FRC can significantly help to increase the stiffness of the laminate without adding too much to its overall weight, giving better load carrying capabilities to the structural material [30].

Hybrid composite materials (HCM) represent the newest group of various composites where more than one type of fibre is used to increase cost-performance effectiveness, i.e., in a composite system reinforced with carbon fibres: the cost can be minimised by reducing its content while maximising the performance by optimal partial replacement with an another fibre or by changing the orientations. HCM include nanocomposites [31], functionally gradient materials [32], Hymats (hybrid materials) [33], interpenetrating polymer networks (IPN) [34], and liquid crystal polymers [35].

More in-depth information about the dispersed phases is given in Section 6.2.3.

6.4.1.3 The Interface and Interphases

The interfaces and interphases between different components and phases in the composite, which is the bounding surface with a discontinuity, has a vital importance in determining final structural properties of the composite. The interfaces and interphases (the interaction and adhesion) between the dispersed phases and matrix are expected to be able to distribute the load evenly that can be borne by the composite [36].

6.4.1.4 Advanced Composites

Advanced composite materials (ACM) were developed during the third quarter of the twentieth century, once special (advanced) high tensile and/or high modulus (and specifically continuous) fibres of carbon, boron, silicon carbide and alumina became available. They are used to reinforce high performance polymers, metal or ceramic matrices [27]. They are a specialised group of composites that have high performances applications under extreme mechanical, electrical and environmental conditions in aircraft/aerospace, construction and leisure or sports. Today, the fraction of carbon fibre composites in large passenger aircrafts like those made by Airbus, and the Boeing 737 or Tu-204/Il-86 has reached 15% of the structure weight and in most military helicopters it exceeded half of the total structure weight. ACM consist of a high strength reinforcing constituent combined with a high performance matrix [37].

6.4.2 Chemical Structure of the Polymer Matrix

Matrices are usually about 30-40% of the composite structure, and can have a number of critical functions: firstly, the matrix helps to bind the reinforcing components together and determines the main thermomechanical stability of the composite, protecting and safeguarding reinforcing components from wear/abrasion and various effects of the environment. The matrix also helps to distribute the applied load by acting as a stress transfer medium. In addition, the matrix provides durability, interlaminar toughness and strength, (i.e., shear/compressive/transverse strengths), to the system, and helps to achieve the desired fibre orientations and spacings in specific composite structures. A high performance matrix resin is expected to have a modulus of at least 3 GPa for strength and a sufficiently high shear modulus (to prevent buckling of fibre reinforcements especially when under compression, although the matrix is known to play a minor role in the tensile load-carrying capacity of a composite). The matrix has a major influence on the interlaminar shear (particularly important for structures under bending loads) and on the in-plane shear (important for structures under torsional loads) properties. Most of the reinforcing components, (i.e., glass, graphite and boron fibres), are all linear elastic and are brittle solids. Whenever they are stressed alone, they show catastrophic failure as a result of growth of an unstable flaw. And although both reinforcing components and the matrices are brittle, their combination can produce a tougher composite material, via the synergism achieved.

In PMC the matrices are polymeric. Low densities leading to low weights and low thermal expansions of these matrices in addition to their high stiffness, strength and fatigue resistances are fulfilled mostly by use of polymeric systems. This gives them properties

comparable with metallics, even with aluminium, and PMC are the most well developed composite materials group. They can be fabricated into any large complex shape, which is the biggest advantage PMC provides.

In PMC applications, either thermosetting or thermoplastic polymers can be used as the matrix component. PMC, also called reinforced plastics (RP) or fibre reinforced plastics (FRP), in general, are in 'a synergistic combination of high performance fibres and matrices'. In these systems, the fibre provides high strengths and moduli while the polymer matrix spreads the load and helps resistance to weathering and to corrosion. Hence, in PMC, strength is almost directly proportional to the basic fibre strength and it can be further improved at the expense of stiffness. Matrix polymers as the raw material usually constitute some 40% of the total cost of the composite, followed by 30% for the fabrication costs.

PMC and in particular FRP composites have generated a lot of interest and there are future expectations for their use in construction in coming years. They are already being used to improve the performance and durability of new as well as deteriorated facilities (for repair/rehabilitation or upgrading), as either 'stand alone' structural members, as reinforcement for concrete, (i.e., as FRP bars or as externally bonded reinforcements, EBR) [38] or in combination with other structural materials. FRP are especially suitable for difficult and complex applications both for load bearing (beams, columns, etc.), or on secondary elements (infill, partition walls and so on) [39].

In PMC, the polymer matrix is expected to wet and bond to the second (reinforcing) constituent, and it is expected to flow easily for complete penetration and elimination of voids in the system. It must be elastic enough with low shrinkage and low thermal expansion coefficients (TEC); it must be easily processable, must have proper chemical resistance, in addition to low and high temperature capabilities, dimensional stability and so on.

Table 6.7 presents some advantages and disadvantages of using thermoplastic and thermosetting PMC.

6.4.2.1 Thermoplastic PMC

Thermoplastic PMC usually have limited use temperatures and they soften upon heating at their T_g which are usually not too high (upwards of 220 °C). However, thermoplastic PMC can be easily and readily processable by use of conventional processing techniques, and they can be reshaped whenever needed. They offer the potential of high toughness

Table 6.7 Thermoset and thermoplastic matrices, prepregs and PMC – their advantage and disadvantages		
Property considered	**Thermoset matrix**	**Thermoplastic matrix**
As Matrix		
Formulation	Complex	Simpler
(Melt) Viscosity	Low (at the beginning)	Rather high
Fibre impregnation	Easier	Very difficult
Overall cost	Low to medium	Low to high
As Prepreg		
Tackiness/drape	Good	Comparably low
Shelf life	Very poor	Good
As Composite		
Processing cycle	Very long	Short to long
Processing temperature and pressure	Moderate	High
Size of products	(Can be very) large	Small to medium
Resistance to solvents	Good	Poor to good
Damage tolerance	Poor to excellent	Fair to good
Resistance to creep	Good	(Not known)
Interlaminar fracture toughness	Low	High
Ease of fabrication	Labour intensive	Less labour intensive

and low cost, high volume processibility for composite structures. The rather large coefficient of thermal expansion (CTE) values of thermoplastic PMC (which may lead to a serious mismatch between dispersed phases and the matrix) and their sensitivities towards certain environmental effects - mostly hygrothermal, i.e., absorption of moisture can cause swelling as well as reduction in T_g leading to accumulation of severe internal stresses in the composite structures, are probably the main disadvantages of these materials in use.

Most commonly used matrix materials for thermoplastic PMC in construction are polyolefinics (PE, PP), vinylic polymers (PVC, PTFE), polyamides (Nylons), polyacetals, polyphenylenes [polyphenylene sulfide (PPS)], polysulfone and poly-ether-ether-ketone (PEEK). All of these are discussed in the first part of this chapter and some of their characteristic properties are presented in **Table 6.8**.

Table 6.8 Typical properties of some thermoplastic matrices							
	LDPE	**HDPE**	**PP**	**PVC**	**Polyamide 6**	**PPS**	**PEEK**
Density ($g.cm^{-3}$)	0.89-0.93	0.94-0.98	0.85-0.92	1.3-1.4	1.15	1.3	1.26-1.32
Elastic modulus (GPa)	0.1-0.3	0.5-1.2	1.0-1.5	2.5-4.0	2.6-3.0	3.3	3.7-4.0
Tensile strength (MPa)	5-25	15-40	25-40	25-70	78	92	70-100
CTE (10^{-5}/°C)	18	12	10	5	12		9.9
Thermal conductivity ($W.m^{-1}.K^{-1}$)	0.33	0.63		0.5	0.31		0.25
Water absorption (24 h %)	< 0.015	<0.01	<0.01	0.4-0.07	2.7	0.2	0.1
T_g (°C)	-110	-90	-15	87	46-60	85	143
Continuous service temperature (°C)	90	120	150	65	100	260	310
LDPE: Low-density polyethylene							

6.4.2.2 Thermosetting PMC

Thermosetting PMC are the most frequently used matrix materials in composites production. Thermosetting PMC are crosslinked materials and they are shaped during the final fabrication step, after which they do not soften by reheating. They are known to have covalently bonded, insoluble and infusible three-dimensional network structures. In order to promote their processabilities, thermosetting resins are applied in the partially cured and usually vitrified system below their gel points (B-stage resin), which is a low molecular weight telehelic reactive oligomer.

During processing of the composite part, the reinforcement, B-stage resin, curing agent and/or hardener are all mixed, pre-shaped and cured completely. For the use of reinforcements in sheet form with approximately 1 mm thicknesses, a special term, 'prepreg' is used (short for 'pre-impregnation') for the mixed, pre-shaped, but as yet uncured system. The stage of the resin in final fully cured and ready-to-use part is called C-stage resin in all cases.

Solidification starts either whenever the components are mixed (at ambient temperatures) or when they are heated at elevated cure temperatures usually in an autoclave (or by other means of curing, such as radiation), which causes a reaction resulting in a rigid, highly crosslinked network or a vitrified system. During curing, there are various intermediate stages from liquid to gel and to the vitrified states as characterised by time - temperature - transformation (TTT) isothermal cure diagrams [40]. From TTT diagrams and rheological or dynamic mechanical data, curing characteristics of thermosetting can be optimised [27].

Thermosetting PMC, because of their three-dimensional fused structures, have higher heat resistances with no softening points, however, their use temperature ranges are still somewhat limited. Thermosetting PMC are also susceptible to environmental degradation to some extent, mainly due to radiation, moisture and even atomic oxygen, (i.e., in space), and they have rather low transverse strengths.

Although the magnitude of environmental degradation, i.e., oxidation, is not as severe as for thermoplastic PMC, there may still be some mismatch in CTE of reinforcement and the thermoset matrix, which may lead to development of residual stresses in the system.

The most common thermoset PMC used in construction and engineering are, polyesters (unsaturated), epoxies, phenolics and polyimides. Information for these will be given in some depth in the following section. Polyesters are extensively used with glass fibres, because they are inexpensive, are somewhat resistant to environmental exposures and are lightweight with useful temperatures up to 100 °C. They are 'low temperature thermoset matrices' that set and are used at ambient temperatures. They are the most widely used class of thermosetting resins used for automotive, various construction and in general for most of the non-aerospace applications. Their poor impact and hot/wet mechanical properties, limited shelf life and high curing shrinkages make them unsuitable for high performance applications. Epoxies are more expensive than polyesters and have lower shrinkage on curing. They are usually set and usable at higher temperatures: 'medium temperature thermosets'. Epoxies show good hot/wet strength, have excellent mechanical properties (especially rigidity) and dimensional stability, good adhesion to a variety of reinforcements and a better moisture resistance, with a slightly higher maximum use temperature (175 °C). A large number of different types and different formulations are available for epoxies. Most of the high performance PMC have epoxies as matrices. Epoxies have applications in the field of construction castings, repair materials, (i.e., to repair and for rehabilitation of damaged bridge decks, expressways and runways), pavements, coatings and structural and non-structural adhesives as well as in decorative floor applications and chemically resistant foams. In these applications, epoxy resins are widely used as polymer concrete or cement in hydraulic construction projects, adhesives, grouting materials, injection glues and sealants. Epoxy resins are used as wall coatings and flooring materials to protect the substrate from chemical corrosion abrasion erosion. They have outstanding adhesion properties and many epoxy systems have been developed to bond to concretes (dry-to-

Table 6.9 Typical properties of some thermosetting matrices				
	Unsaturated		Thermoset	
	Polyester	Epoxy	Polyimide	Phenolics
Elastic modulus (GPa)	2.1-4.4	2.8-4.2	3.2	2.8-4.8
Tensile strength (MPa)	15-90	35-100	55-120	35-62
CTE (10^{-5}/°C)	10	4.5-11	5-9	4
Thermal conductivity ($W.m^{-1}.K^{-1}$)	0.2-0.3	0.17- 0.23	0.36	
Water absorption (24 h %)	0.15	0.1	0.3	0.15
T_g (°C)		130-250	370	
Continuous service temperature	120	25-85	260-300	200-300

dry 'old' or in dry-to-wet 'new' concrete). Phenolics are also 'medium temperature thermosets'. Polyimides and bis-maleimides are more difficult to fabricate, as they have much higher use temperatures (300 °C), and are 'high temperature thermosets'.

Some of the characteristic properties of thermosetting PMC are presented in the **Table 6.9**.

Flammability characteristics of composites are outlined in Chapter 6, (Section 6.4.2).

6.4.2.3 Epoxy Resin Chemistry

Low molecular weight organic liquid resins with a number of three membered rings with one oxygen and two carbon atoms (called epoxide groups, **Figure 6.16**) are the starting materials for the epoxy matrix.

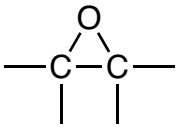


Figure 6.16 Characteristic group for epoxy resins

Epoxides can be simply difunctional or polyfunctional. The most widely used version is the difunctional epoxy type: diglycidyl ether of bisphenol A, with (*n*) from 0.2 to 12 (**formula 1 in Figure 6.17**) which can be used with different types of curing agents, (i.e., various amines). Epoxidised novolaks (**formula 2 in Figure 6.17**) have multi-

epoxy functionalities (where there are at least two or more epoxy groups per molecule). While for higher temperature applications, a special polyfunctional epoxy with aromatic and heterocyclic glycidyl amine groups, i.e., tetraglycidyl methylene dianiline (TGMDA; **formula 3 in Figure 6.17**) is generally used. New generation aromatic and glycidyl amine resins with improved hot/wet temperature characteristics (**formulae 4 and 5 in Figure 6.17**), as well as a number of special multi-functional epoxides formulated with TGMDA and/or bisphenol A, (**formula 1 in Figure 6.17**) are also available.

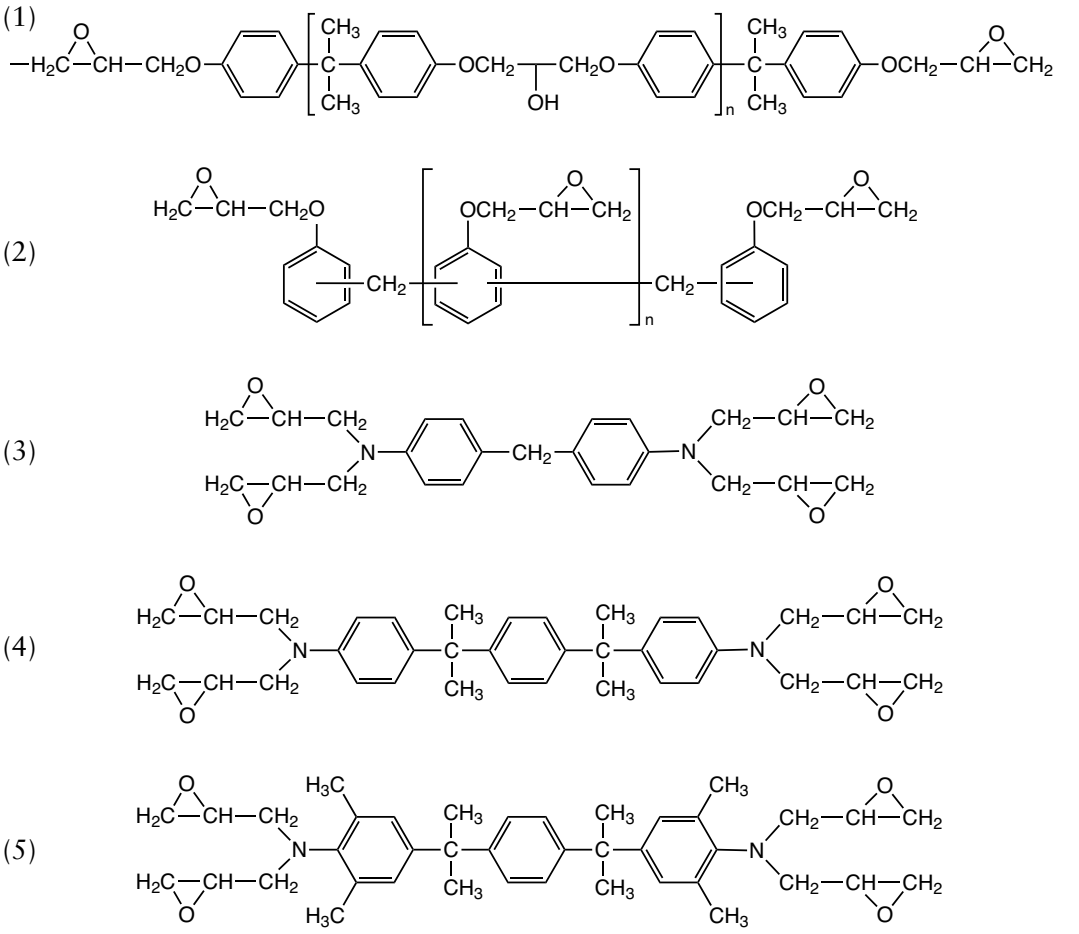


Figure 6.17 Diglycidyl ether of bisphenol A (formula 1), an epoxidised novolak formula 2), TGMDA (formula 3) and new generation (aromatic and glycidyl) amine resins (formulae 4 and 5)

Curing agents used for epoxides can either be incorporated with the epoxide directly or can act as a catalyst to promote crosslinking. For the former, they are usually polyfunctional and basic or acidic. Primary/secondary amines, and polyaminoamides are examples of polyfunctional and basic while anhydrides, polyphenols, polymeric thiols are the most common polyfunctional and acidic curing agents used. Depending on the basicity or acidity of curing agent, curing may occur at room or at high temperatures. Curing agents that promote crosslinking are also known as 'catalytic curing agents', such as tertiary amines and BF3 complexes and they can accelerate curing both at low or at ambient temperatures).

There is usually a compromise between the use temperature and toughness for final epoxides produced, i.e., if the use temperature is high (247 °C), the epoxy is brittle. Whereas the use temperature is much lower for the toughened epoxides), and the degree of polymerisations are also found to affect crosslink densities [40], and hence processability. The type of curing agent or accelerator and their molar ratio to the epoxy effects final crosslink densities of the system and they must be optimised (for structural applications, a special hardener dicy-dicyandiamide is widely used). There are a number of different methods and strategies already available [41] and there is a considerable amount of research available as regards further improvement of toughness [40, 37], moisture resistance and heat stability of epoxy matrices. These studies led to epoxy composite systems with the desired tensile - compressive moduli and tensile strength values of 138 GPa and 1930 MPa (3100 MPa and 96 MPa for the neat resin), respectively [31].

Epoxy resins have the added advantage over many other thermosets in that, since no volatiles and condensation products other than the polymer product are produced during cure, moulding does not require, in principle, high pressure moulding equipment.

By using an epoxy matrix, one can gain a system with following advantages:

(a) a wide variety of properties,

(b) low shrinkage during cure, lowest within other thermosets,

(c) good resistance to most chemicals,

(d) good adhesion to most fibres, fillers,

(e) good resistance to creep and fatigue, and

(f) good electrical properties.

and with following principal disadvantages:

(a) sensitivity to moisture (after moisture absorption (1-6%), there is usually a decrease in the following: heat distortion point, dimensions and physical properties),

(b) difficulty in combining toughness and high temperature resistances, as explained previously,

(c) high TEC as compared to other thermosets,

(d) susceptibility to UV degradation, and,

(e) cost - epoxies are more expensive than polyesters.

6.4.2.4 Polyester (Unsaturated) Chemistry

Unsaturated polyesters are the most versatile class of thermosetting polymers. They are macromolecules made up of an unsaturated component, (i.e., maleic anhydride or its trans isomer, fumaric acid, which provides the sites for further reaction) and a saturated dibasic acid or anhydride with dihydric alcohols or oxides (typically phthalic anhydride which can be replaced by aliphatic acid, like adipic acid, for improved flexibility). If blends of phthalic anydride (or isophthalic acid) and maleic anhydride/fumaric acid are used, 'ortho (or iso) resins' (**Figure 6.18**) are obtained. On the other hand, if propoxylated or ethoxylated bisphenol A is used with fumaric acid, 'bisphenol A fumarates' are obtained, if a blend of chlorendic

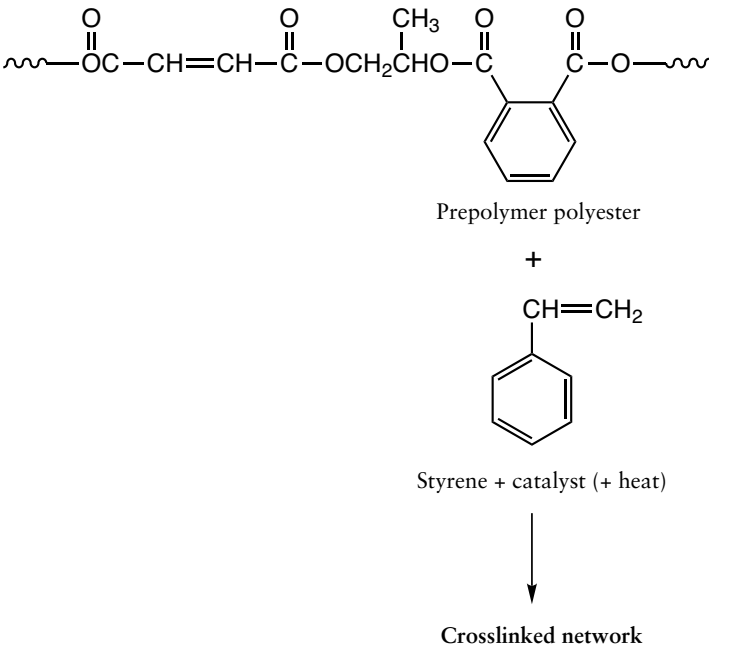


Figure 6.18 Production of an (ortho) unsaturated polyester crosslinked matrix

anhydride or chlorendic acid and 'maleic anhydride/fumaric acid' are used, 'chlorendics' are obtained. Within these, biphenol A fumarates are unique for high performance and chlorendics are for improved flame resistance applications. If the unsaturated resin is prepared by the reaction of a monofunctional unsaturated acid, (i.e., methacrylic or acrylic acid), with a biphenol diepoxide, a new family of polyesters which are called 'vinyl resins' with exceptional mechanical and thermal properties is obtained [36].

The unsaturated polyester matrix is prepared as follows: in most cases, the polymer (polyester) is dissolved in a reactive vinyl monomer, (i.e., styrene) to give a proper (solution) viscosity. The resin is cured by use of a free radical catalyst, decomposition rate of which determines the curing time (and curing times, in general, can be decreased by increasing the temperature). For a high temperature cure, say at 100 °C, benzoyl peroxide is commonly used, whereas for room temperature cure, other peroxides with metal salt accelerators are preferred. A crosslinking reaction occurs between the unsaturated polymer and the unsaturated monomer, converting the low viscosity solution into a highly viscous, and finally to a solid three-dimensional network system. Crosslink densities can change (by direct proportionality) the modulus, the value of T_g and thermal stabilities, and (by inverse proportionality), strain to failure and impact energies. The formation of the final crosslinked structure can be accompanied by considerable volume contractions (7-27%).

Polyesters, as matrix materials, have rather good tensile and flexural strength values and their sensitivities to brittle fractures can be improved and even can be eliminated, after application of extensive annealing treatment [41]. Because of the high content of aromatic vinyl groups, the crosslinked polyester is easily susceptible to thermooxidative decomposition, which reduces the long-term use temperature. In general they have good chemical and corrosion resistance, and also have good outdoor resistances. As in the case of epoxides, polyesters have the added advantage over many other thermosets that, since no volatiles and condensation products other than the polymer product are produced during cure, moulding does not require, in principle, high pressure moulding equipment. **Table 6.10** shows some characteristics of polyester and epoxy thermosets.

6.4.2.5 Chemistry of Polyimides and Bismaleimides

Polyimides can be thermosets (condensation) or thermoplastics. Thermosetting polyimides are products of a 'diamine' and a 'dianhydrate of a tetracarboxylic acid' in polar solvents, which first gives a polyamic acid. The removal of water yields polyimides. The polyimide matrices are mostly used in high performance advanced composite applications. Polyimides contain (-CO-NR-CO-) groups as linear or heterocyclic units along the polymer backbone. They may be translucent or opaque. A condensation polyimide is shown in **Figure 6.19**. Their tensile and flexural strengths are commonly around 110 and 200 MPa, respectively.

Table 6.10 Some characteristics of epoxy and polyester thermosets	
Characteristics	**Some Limitations**
Epoxy matrices: 'medium temperature thermosets'	
Good electrical properties	Curing at high temperatures for maximum performance
Good chemical resistance	High cost
Good adhesion	Moisture sensitivity
High strengths	High TEC
Very low shrinkage on cure	
Unsaturated polyester matrices: 'low temperature thermosets'	
Good all-around properties	Ease of degradation
Ease of fabrication	Useful temperatures up to 100 °C
Low cost, versatility	Poor impact properties limited shelf life

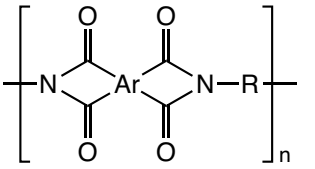


Figure 6.19 A condensation polyimide

Aromatic, heterocyclic polyimides (**Figure 6.20**) have outstanding mechanical properties and thermal-oxidative stabilities. They are mostly used for high performance applications in place of metals and glass. However, they have one disadvantage: their price is rather high.

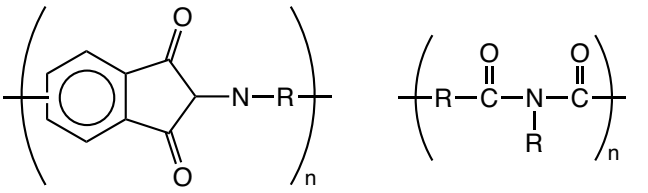


Figure 6.20 An aromatic, heterocyclic polyimide

Bismaleimides (**Figure 6.21**) can be considered as structurally modified polyimides, or as PMR (polymerisation of monomer reactants) [41], or addition polyimides (obtained by using end-capped imide oligomers with unsaturated functional groups like olefins, norbornene, acetylene or maleimide. The thermally induced crosslinking reaction occurs via a free radical mechanism across the terminal double bonds, which can react with themselves or with other co-reactants (such as vinyl, allyl or other functionalities). PMR were developed as the result of 'the demanding requirements' of the aerospace industries, in particular. They are materials with low flammability, high strength and high mechanical and thermal integrity at high temperatures in aggressive environments for prolonged periods of time with inherent brittlenesses, which are modified by use of several thermoplastics to increase its toughness.

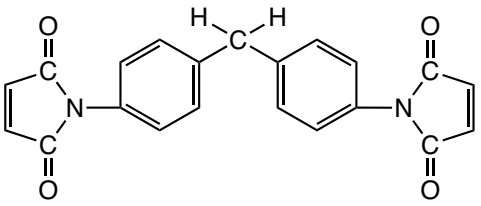


Figure 6.21 A bismalemide

6.2.2.6 Brief Chemistry of Phenolics

The most commonly known phenolic composite group is phenol formaldehyde polymers (phenoplasts). They are produced by polycondensation of a phenol and a mixture of phenols (phenol and phenol derivatives like cresol-resorcinol or *para* tertiary butyl phenol) with an aldehyde, usually formaldehyde and hexamethylene tetramine. Reaction of formaldehyde with phenol (up to 3 moles of formaldehyde can react with one mole of phenol - phenol acts as a three functional monomer) yields methylol groups in the *ortho* and *para* positions of the phenol molecule. In a further reaction, the methylol groups condenses with another molecule of phenol to form a methylene bridge. In practice, a prepolymer (usually a powder) is prepared first which is then cured later to the shape of the article in the mould.

There are two types of phenolic:

(a) One stage polymers (resoles) are produced using an alkaline catalyst with phenol and formaldehyde mixed in proper proportions. The polymer is a thermoset and heat reactive which further heating (to complete the reaction) produces an infusible, insoluble, highly crosslinked structure.

(b) Two stage polymers (novolacs) are produced using an acid catalyst, where only part of the formaldehyde is used in the system. After discharging the fusible thermoplastic resin, more formaldehyde is added and the final infusible insoluble polymer is obtained.

Both one and two stage polymers are used individually or in combination in applications. The final insoluble and infusible phenol-formaldehyde resins are called Bakelite [1]. Phenol-formaldehyde resins are good electrical insulators, they are resistant to heat and chemical attack. However, they are brittle and their mechanical properties are not too good.

6.4.3 Structure of Reinforcing Components

In composites, there is usually a substantial volume fraction of high strength, high stiffness reinforcing components dispersed in a lower modulus matrix. The properties of composites strongly depend on the properties of both constituent phases (reinforcing and matrix), as well as on their relative amounts, and geometry of the reinforcing phase, (i.e., shape of the reinforcing component and size, their distribution and orientation). As mentioned previously, the reinforcing component can be discontinuous (either in the form of dispersions/particles, flakes, whiskers, discontinuous short fibres with different aspect ratios) or continuous (long fibres and sheets), particulate and fibrous forms being the most common in use. In fact, PMC can simply be classified into three groups, as:

(a) Particle (or particulate) reinforced composites which have a equiaxed (distributed in all directions) reinforcing phase (where particle dimensions are approximately the same in all directions) with spherical, rod, flake-like and other shapes of reinforcing components with roughly equal axes. Simple filled systems (that are used mostly for cost reduction purposes there is no reinforcement) cannot be considered as particulate reinforced and the same applies for the particles added for nonstructural purposes, i.e., flame retarders and so on.

(b) Fibre reinforced composites, where the dispersed phase is fibrous with a larger length-to-diameter (aspect) ratio, and,

(c) Structural composites [42]. At least two sub-divisions exist, for in each of the first two of these there is always the possibility of change of shape (and even the size) of particulates and size of fibres depending on the type of processing used during the processing stage, while the third one in this classification can be a combination of composites and homogeneous materials, (i.e., laminates and sandwich panels). Usually materials in fibre form are much stronger and stiffer than any other form and mainly for this reason, there is usually an overwhelming attraction for the fibre reinforcements.

6.4.3.1 Particulate Reinforced Composite Systems

Particulates have similar length and breadths with aspect ratios (ratio of length to breadth) around '1' with regular shape, such as spheres, as well as those with irregular shapes, that may have extensive convolution and porosity. Particulates (or particles) are the most common and cheapest and can have various effects on the final mechanical properties of matrix: if ductile particles are added to a brittle matrix, usually an increase in the toughness, as cracks have difficulty in passing through them, i.e., rubber modified polystyrene (HIPS) and epoxy systems [43, 44, 45]. However, if the particles added are hard and stiff, (i.e., have high moduli), and are used in a ductile matrix, an increase in the strength and stiffness values are observed in general, as in the carbon black added to rubber, decreasing the fracture toughness of the ductile matrix somewhat. Particulates help to produce the most isotropic state for composite structures.

Particle reinforced composite systems can be either 'large particle' or 'dispersion' strengthened. If a composite is reinforced by large particles (larger than 0.1 μm and equiaxed, which are harder and stiffer than the matrix), mechanical properties are dependent on volume fractions of both components and are enhanced by increase of particulate content. Concrete is a common large particle strengthened composite where both matrix and particulate phases are ceramic materials.

Whereas in dispersion strengthened composites, dispersed particle sizes are smaller (0.01-0.1 μm) and the matrix bears the main load. In such systems, small dispersed particles obstruct and hinder the motion of dislocations in the matrix. As a result plastic deformations are restricted. In dispersion strengthened composites both yield and tensile strengths as well as hardnesses are improved where particle-matrix interactions are on the molecular, or even on the atomic, level. Elastomers and rubbers are usually reinforced with various particulate components, i.e., carbon black consisting of very small (diameters 0.02-0.05 μm) essentially spherical particles are efficient reinforcing components for vulcanised rubber, enhancing tensile strength, toughness, tear and abrasion resistances.

6.4.3.2 Fibre Reinforced Composite (FRC) Systems

Fibre, by definition, means a single, continuous material whose length is at least 200 times its width (or diameter), and filaments are endless or continuous fibres. FRC are widely used in structural applications because of the high specific moduli (the ratio of elasticity modulus to specific gravity) and/or high specific strengths (the ratio of tensile strength to specific gravity) they provide. In FRC, the dispersed fibre phase bears the main load and the matrix is confined mainly to load distribution (and its transfer to the fibres as well so as to hold the fibres in place). In FRC, the organic matrix phase is also expected to coat the

fibre surfaces, and the interactions involved at interfaces are physical. Proper adhesion between fibres and the matrix is very important as explained previously, to let the matrix carry the stress. This is of utmost importance if a fibre breaks or its size gets smaller.

Fibres that are used in FRC can be natural (mostly organic fibres from plants, such as cellulosics or inorganic natural fibres such as asbestos, which is no longer used due to the health hazards involved, and glass fibres) or synthetic (aramids - Kevlar and Nomex, high and ultra-high modulus PE with moduli in the range of 50-100 GPa, about ten times that of normal textile fibres), PP and carbon fibres, all applied either as woven or non-woven fabrics, fibres or rovings in either discontinuous or continuous form. Synthetics are usually more uniform in size and are economical to use.

The global market for advanced composites consumes over 140,000 tonnes/year of fibre reinforcements (of carbon, aramid, high modulus PE, boron, various types of glass fibres).

6.4.3.3 Glass Fibres

Glass is an amorphous material composed of a silica network and it has been known since the time of the ancient Egyptians [33]. Commercially there are four main classes of glass used in fibre form: high alkali, A glass grade (essentially soda-lime-silica), electrical, E glass grade (a calcium alumino-borosilicate with low alkali oxide content), chemically resistant, modified E glass grade (with calcium alumino-silicate; ECR glass) and high strength, S glass grade (with magnesium alumino-silicate and no boron oxide). Within these, E glass fibre is the most widely used for reinforcement, although S grade has the highest tensile strength and elastic modulus (**Table 6.11**). Glass fibre is spun from the melt and it is obtained after cooling in the final solid condition without letting it crystallise. After their production, fibres are transformed into finished forms (as either continuous or woven rovings, chopped strands or fibreglass mats and preforms) and a proper fibre sizing (fibre finishing or application of a coupling agent) is applied to facilitate the interaction with matrix, to protect them from damage during processing and to aid the processing. They can be proper film forming organics and polymers or adhesion promoters (like silane coupling agents) [35].

Table 6.11 presents some mechanical properties of different types of glass fibres.

6.4.3.4 Carbon Fibres

Carbon fibres have been known for more than 100 years, however, only after 1950s, did they become more common after the increase of interest for high strength and light

Table 6.11 Some properties of different reinforcing fibres				
	Density (g/cm^3)	**Tensile strength (GPa)**	**Young's modulus (GPa)**	**Strain to failure (%)**
Glass Fibres (provide: low dielectric properties, better insulation, heat formability)				
E-Glass	2.62	3.45	81	4.9
S-Glass	2.50	4.59	89	5.0
A-Glass	2.50	3.05	69	5.0
Para-Aramid Fibres (provide: low flammability, low CTE, low de, insulation)				
Kevlar 29 (high toughness)	1.44	3.0-3.6	85	4.0
Kevlar 49 (high modulus)	1.44	13.6-4	131	2.8
Kevlar 149 (ultra high modulus)	1.47	3.5	186	2.0
Carbon Fibres (provide: dimensional stability and retention, performance at high temperatures, very low CTE, tailorable thermal conductivity, high shear modulus)				
PAN (high modulus)	1.9-3.7	350-550		0.4-0.7
PAN (int modulus)	3.1-4.4	230-300		1.3-1.6
PAN (high strength)	4.3-7.1	240-300		1.7-2.4
de: dielectric constant				

weight reinforcements. They are obtained by the pyrolysis of certain organic precursor fibres such as rayon, polyacrylonitrile (PAN) or pitch. They are carbonised between 1200-1400 °C and they contain 92-95% carbon. After carbonisation, tensile strength values of 3000 MPa and moduli of 250 GPa (and even higher) are usually achieved, the latter of which even can be improved up to 350 GPa at the expense of some drop in strength by post treatment. Carbon fibres are used as yarn, felt or powder-like short monofilaments with diameters smaller than 10 μm. There are different types of carbon fibres depending on origin of precursor, such as:

(a) PAN-based,

(b) Isotropic pitch based,

(c) Anisotropic pitch based,

(d) Rayon based, and,

(e) Gas phase grown [28].

Depending on their mechanical properties, carbon fibres can be classified into four groups:

(a) PAN-based high modulus (HM), low strain to failure type,

(b) PAN-based high tensile (HT), high strain to failure type,

(c) PAN-based intermediate modulus (IM) type, and

(d) Mesophase (pitch) based.

The third of these belong to the HT type with high tensile strength and improved stiffness. **Table 6.11** shows some mechanical properties of different types of carbon fibres.

6.4.3.5 Aramid/Kevlar Fibres

Aramids are aromatic polyamides. The two commonest members of this family are Kevlar (*para*-phenyleneterephtalamide, PPA) and Nomex (polymetaphenylene, PPD), which were introduced in the early 1970s. Kevlar has an aromatic ring structure which contributes to high thermal stability and the para configuration leads to rigid molecules that contribute to high strength and modulus. Kevlar is a liquid crystalline material. When Kevlar is extruded into fibre form, a highly anisotropic structure with a high degree of alignment of straight polymer chains develops, giving rise to higher strength and modulus in longitudinal direction of the fibre. In addition, there is fibrillation in the structure which is believed to have a very strong effect on fibre properties and failure mechanisms. Some advantages of using Kevlar are: they are tough and have good damage tolerances and do not have a conventional melting point or a T_g (estimated as >375 °C). In turn, Kevlar decomposes (in air) at around 425 °C and they are flame resistant. Para-aramid fibres have a small but negative longitudinal (and a bigger positive transverse) TEC value. Kevlar fibre can be degraded chemically only by strong acids or bases, in addition to UV radiation. There are different types of Kevlar - Kevlar 29 (with high toughness), Kevlar 149 (with ultra high modulus) and Kevlar 49 (with high modulus). In structural composite production, Kevlar 49 is mostly used. Different short fibre forms and yarn counts of Kevlar fibres are also available. For Kevlar fibres, moduli ranges between 85-186 GPa while tensile strengths are around 3.4-4 GPa, the latter of which is more than twice the strength of Nylon 66 and 50% greater than that of E-glass.

6.4.3.6 Other Natural and Synthetic Polymeric Reinforcing Fibres

Natural polymeric fibres, mostly cellulosics, have been used since ancient times for reinforcement. Mechanical properties of these are inferior to glass, carbon or aramid fibres. Cellulosics are usually used as a laminating material, in the woven form. Processing

wood plastic composites (WPC) into profiles for building and construction applications is currently one of the most exciting businesses in extrusion. After the availability of synthetics, (i.e., polyamides, acrylics, polyolefins, etc.), and in particular, with ultra-high modulus fibres later, new generation of synthetic fibres with high moduli (ultra-high modulus fibres of 50-100 GPa, the value of which is about ten times those of conventional fibres) are achieved. Recent introduction of polyether imide (PEI) fibres by Akzo (Enka) offer high temperature and good environmental resistances while paraphenylene polybenzobisoxazole, (PBO) fibres by Dow have a unique combination of high strength, stiffness and environmental resistance, which offers high tensile strength and modulus values that are better than Kevlar. There is also the family of polybenzazoles (PBZ), which have good strength and moduli values.

Within these fibres, polypropylene fibres were used successfully to reinforce cement-based materials.

6.4.3.7 Use of Reinforcing Polymeric Fibres in Concrete

There is a considerable interest in use of polymeric fibres as reinforcements in concrete (FRP reinforcement [46]) and as structural shapes for building construction, to improve the performance of new constructions or deteriorated constructions for repair and rehabilitation. These applications are limited to bars and laminates for the time being. Polymeric fibre reinforced bars are currently being used as the internal reinforcement in concrete members (when the steel bars may not (desired, e.g., due to corrosion) [47, 48]. Strengthening of concrete with externally bonded reinforced (EBR) FRP composites in the form of laminates or near surface mounted bars (NSM) to repair and strengthen existing structures is becoming a more established practice worldwide, specifically for restoration of historical structures mainly due to their ease of application [49]. In either application, the use of FRP as structural reinforcement is accepted as a viable alternative to classical types of reinforcement with many potentials offered. The use of FRP in concrete structures started some 25 years ago in Europe, and resulted for example in the first highway bridge in the world with FRP post tensioning cables in Germany in 1986 and structural FRP shapes in the Aberfeldy bridge in Scotland in 1992, where glass fibre and aramid reinforced structural elements were used in the deck and towers bonded with epoxy. And the recent all composite bridge suitable for heavy traffic being built in Den Dungen in the Netherlands. The FRP reinforcement market today is much larger and more developed in North America and Japan. In both, the bulk of FRP applications are related to both reinforcing (as a substitute for steel) and for upgrading (retrofitting and repairing) studies, particularly for strengthening of slabs, beams and columns in buildings. Some design guidelines on the use of FRP rods [49] and sheets are available [50]. One disadvantage of FRP bars are their unfavourable economy at the moment. Most glass

fibre reinforced bar applications are in 'cosmetic concrete' or in constituent matrices other than Portland cement. Although they are used as top mat reinforcing for bridge decks and seismic upgrading of masonry, they are commonly in demand in magnetic resonance imaging areas in hospitals due to their magnetic transparency. They are used in high voltage substations and reactive transformer pads as well as in airports and in radio frequency research labs for their electrical neutrality.

6.4.3.8 Different Reinforcing Fibre Forms

Depending on the final properties to be achieved and the processing method to be used, reinforcing fibres can be utilised in a number of different forms, i.e., as continuous or chopped. In the continuous form, individual filaments are usually available as a collection of untwisted, parallel, 12 to 120 continuous individual strands (called rovings or tows). Continuous rovings are used in several polymeric composite processes, such as filament winding and pultrusion. For the twisted collection of filaments, the term yarn is used [51]. The most familiar forms of continuous fibres are woven rovings and woven yarns. Woven rovings and woven yarns can be either interwoven to produce braids, while knits can be obtained by interloping chains of rovings and yarns [37]. Filament winding and pultrusion processes are used to produce pipes, tanks and structural composites, whereas rovings are passed through a resin bath and then shaped by winding the resin-impregnated roving onto a mandrel or by pulling it through a heated die. Chopped strands with short lengths of between 3 to 50 mm long are used with different sizings to enhance compatibility with most plastics. Chopped strands are used in a spray-up process where chopped strands are sprayed simultaneously with liquid resin to build up reinforced thermoset parts on the mould [52] or in the injection moulding industry, as well as in sheet and bulk moulding.

Fibres can also be prepared in the form of a mat consisting of randomly oriented short fibres held loosely together by a chemical binder, sometimes in a carrier fabric, as a continuous thin flat sheet. Mats are commercially available as blankets of various weights, thickness, and widths, which can be cut and shaped for use as preforms in some closed-mould processes and in hand lay-up, press moulding, bag moulding, autoclave moulding, and in various continuous impregnating processes.

Cut and shaped fibre forms ready for reinforcement are called preforms. During the preforming process, dimensional materials, (e.g., mats, woven yarns, prepregs, etc.), are converted into three-dimensional shapes. While prepregs are continuous unidirectional or woven fibres (mainly aramid, carbon, and glass) pre-coated with a controlled quantity of an uncured catalysed resin matrix material (mostly epoxy, bismaleimide, phenolic, or polyimide resin) [30], that are supplied in roll or sheet form and ready for immediate use. The predominant methods of prepreg production are via a hot melt or a solvent impregnation. Prepregs are widely used for high-performance structural applications [15].

6.4.4 On The Mechanics of PMC

Mechanical properties of PMC are strongly influenced by the filler (by its size, type, concentration and dispersion) and by the properties of the matrix, as well as the extent of interfacial interactions and adhesion between them and their micro-structural configurations. The interrelation of these variables is rather complex. In FRC, the system is anisotropic where fibres are usually oriented uniaxially or randomly in a plane during the fabrication of the composite, and properties are dependent on the direction of measurement. Generally, 'the rule of mixture' equations are used to predict the elastic modulus of a composite with uniaxially oriented (continuous) fibres under iso-strain conditions for the upper bound 'longitudinal modulus in the orientation direction' (**Equation 6.10**).

$$E_c = [E_m V_m] + [E_p V_p] \tag{6.10}$$

as well as lower bound 'transverse modulus in the direction perpendicular to orientation', for iso-stress condition (**Equation 6.11**) (and by assuming that the strains involved are small, deformations for matrix and fibre are both elastic and they both have the same Poisson's ratio and that there is no de-bonding).

$$[E'_c]^{-1} = V_m[E_m]^{-1} + V_p[E_p]^{-1} \tag{6.11}$$

where E, E´ and V are tensile, Young's (longitudinal and transverse) and volume fraction, respectively; whereas subscripts c, m, p represent the composite, the matrix and the particulate (fibre) components.

More specifically, transverse modulus is given by the modified Halpin-Tsai equation (**Equation 6.12**):

$$[E'_c / E_c] = [1 + AB\ V_p] / [1 - B\Psi\ V_p] \tag{6.12}$$

where A is a constant depending on filler geometry and the Poisson's ratio of the matrix (A is equal to twice the aspect ratio for uniaxially oriented fibres), B is a constant, changing as a function of A and relative moduli of the filler and matrix, and Ψ is a constant that depends on maximum packing volume fraction of the filler [53-58].

Large particle reinforced composite systems are utilised with all three types of materials (metals, ceramics and polymers). Concrete is a common large particle strengthened composite where both matrix and particulate phases are ceramic materials.

Composite strength is not as easily modelled as modulus as it depends on a number of factors such as the extent of interaction between matrix and fillers. As interfacial strength

can be affected and reduced by the presence of water as it is adsorbed on the filler surface or by thermal stresses from mismatch between CTE values of the filler and the matrix. In fact there is an order of magnitude difference between CTE values of polymers and glass, formulation of composite strength becomes more difficult and complex. For composite bars, the design tensile strengths that should be used in design equations, is calculated as:

(design tensile strength of product) = (environmental design factor)
× (tensile strength of the bar)

Where the environmental design factor is given for different fibre types and exposure conditions, i.e., for glass fibre (GF) for interiors it is 0.85 and for both exterior/aggressive environment, 0.85 [48, 59].

As a final note, the 'FRP-ConstruNet' initiative sponsored by EU into the 6th Framework Programme Network must be mentioned, which is created under the construction industry initiative and it is technological, commercial - scientific and technologically oriented.

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7 Plastics and Polymer Composites: A Perspective on Properties Related to their use in Construction

Dorel Feldman

7.1 Foams

Polymer foams, also known as cellular polymers or cellular plastics, are multi-phase material systems (composites) that consist of a polymer matrix and a fluid phase, one usually being a gas. Foam is a general term that refers to a material with any degree of communication between its voids. The word cellular is used as a general term whereby the cells may have any degree of interconnection - expanded polymers are composites with closed cells.

The rapid upsurge of interest in lightweight materials during the last few decades has inevitably brought cellular polymers into prominence. These polymers offer an attractive combination of properties, often at low cost and the types of material and range of applications is increasing rapidly. It is estimated that in 2000 close to 3.5 billion tons of polymer foams were produced and consumed in USA. Their annual growth is estimated at 3-4%, most of which is in the construction, automotive, packaging and consumer product market [1].

Polymer foams have entered the construction industry by direct replacement of conventional thermal insulation materials. Most foam can be made with a large spectrum of properties, densities and shapes to fulfil specifications. Nowadays it is possible to foam virtually any polymer since a lot of the basic principles governing the foaming technology and its operations are applicable to a large number of macromolecular compounds, but only a small number have been commercially exploited. Polymer foams are made of thermoplastics or thermosets. While the former can be reprocessed and recycled, the thermoset foams are intractable since they have a high degree of crosslinking. Even recycled polymers can be used for foam manufacturing [2]. **Table 7.1** shows some examples of thermoplastic and thermosetting foams.

The foams that dominate the market are made of polystyrene (PS), polyurethane (PU) and polyvinyl chloride (PVC). Phenolic foams are also used in a significant volume. These and PVC foam are becoming more interesting because of their low flammability characteristics. However, over the last few years there has been an increasing utilisation

Table 7.1 Some thermoplastic and thermosetting foams		
Type of polymer	**Mode of synthesis**	**Mechanical properties**
PVC	Polymerisation	Flexible and rigid
PS	Polymerisation	Rigid
PU	Polyaddition	Flexible and rigid
PIR	Cyclotrimerisation	Rigid
Polyamide	Polycondensation	Flexible and rigid
Polyimide	Polycondensation	Semirigid
Phenolics (PF)	Polycondensation	Rigid
Aminoplasts (UF)	Polycondensation	Rigid
Polyurea	Polyaddition	Flexible and rigid
Epoxy (EP)	Ring-opening polymerisation	Rigid
UF: urea-formaldehyde		

of engineering structural foams for load bearing applications. The polymers used include polyisocyanurate (PIR), polyolefins, modified polyphenylene oxide, polycarbonate (PC), and acrylonitrile-butadiene-styrene terpolymer (ABS).

Polyimide characterised by thermal and thermal-oxidative stability at elevated temperatures, chemical resistance and good mechanical properties is relatively new in the family of polymer foams [3]. In some cases, depending on the uses, additional reinforcement can be included. Examples are fibre reinforced foams and syntactic foams which are composites containing hollow glass, ceramic or plastic micro-spheres dispersed throughout the polymer matrix.

Due to their complex nature, polymer foams have been classified following different criteria such as:

(a) Composition (which refers to the kind of polymer the matrix is),

(b) Cellular morphology (open cell or closed cell), mechanical behaviour (rigid or flexible),

(c) Density (low density range 10-50 kg/m^3, medium density range 50-350 kg/m^3, high density range 350-900 kg/m^3).

The open cell foams have a cellular network and the voids coalesce so that the solid (polymer matrix) and the fluid phases are continuous [4].

At present, there are at least two approaches to the investigation of the cellular structure of foamed polymers. In the first one, which may be formally called a graphical approach, attempts are made to draw conclusions about the macroscopic properties from morphological parameters such as geometry and stereometry of cells of various sizes and shapes. The second approach, which may be referred to as physico-chemical, attempts to explain and predict the morphology from the data of the chemical composition of the matrix and the mechanism of foaming [3].

In practice, the two cellular morphologies can co-exist so that polymer foam is not always completely open or closed cell. The volume fraction of closed cells has a considerable influence on the mechanical properties of these systems so it is an important structural characteristic. Ways to characterise and measure morphology that affects the solid and heat radiative contributions in closed cell foams have been recently developed [4].

Rigid foams can be crystalline, semi-crystalline or amorphous; in the last case, its state (glassy) is below its glass transition temperature (T_g), and the properties depend highly on the existence of some crystalline domains and the extent of crosslinking. A flexible cellular polymer is a system in which the matrix is in a state (high elastic) above its T_g. Most polyolefins, PS, phenolics, PC, polyphenylene oxide and some PU foams are rigid, whereas rubber foams, elastomeric PU, certain polyolefins and plasticised PVC are flexible. Intermediate between the two extremes is a class of semi-rigid foams.

The rigid cellular foams can be further subdivided into:

- Non-load bearing (non-structural foams) applications, such as thermal insulation, or
- Load bearing (structural foams) structural materials, which require high stiffness, strength and impact resistance.

Rigid foams are used mainly in building and construction, for insulation, tanks, pipes, etc.

From the structural point of view some foams can be homogeneous with a uniform cellular morphology or they may be structurally anisotropic. They may have an integral solid polymer skin [5] or they may be multi component in which case the polymer skin is of different composition to that of the polymeric cellular core.

Microcellular polymers produced by gas nucleation, refer to closed cell thermoplastic foams with a very large number of very small cells (of the order of 10 mm in diameter), typically 10^8 or more cells per cm^3. Microcellular thermoplastics have been obtained from a number of different polymers, ranging in relative density from 0.1 to 1.0 kg/m^3, containing 10^8 to 10^{10} cells per cm^3, offering a new range of properties for design [6, 7]. For example microcellular PU foams can be obtained via polymerisation in carbon dioxide [8, 9].

Most polymer foams are produced by one of the several known foaming techniques which include, extrusion, compression moulding, injection moulding, reaction injection moulding, thermoforming, solid state technique (where pressurised gas is forced into a solid polymer at room temperature followed by depressurisation and heating to above the T_g of the polymer), spraying and so on [10, 11].

7.1.1 Foaming (Blowing) Agents

The gas phase in any polymer foam derives from the use of foaming (or blowing) agents in the foam manufacturing process. In foam production, foaming agents and, in many cases, other auxiliary substances are added to the polymer. These components must be mixed very thoroughly to prevent defects and irregularities in the foam. As foaming starts, the mixture must be able to flow freely. Once the bubbles formed have attained the desired size they must be fixed. This is accomplished through the hardening of the polymer. The resultant cellular body is a solid-gas composite consisting of a continuous polymer phase and a gas phase either continuous or discrete created by the foaming agent. Depending on the nature of the cell-forming process, that is, whether it is a physical change of state or a chemical decomposition, blowing agents are classified as physical or chemical.

7.1.1.1 Physical Foaming Agents (Gaseous or Liquid)

Nitrogen, air, carbon dioxide, a mixture of air and helium, are examples of gaseous foaming agents used in the production of polymer foams. Nitrogen and air are preferred since they are inert, nontoxic, non-flammable and have a low diffusivity with respect to the majority of polymers. An air/helium mixture permits an easy control of the foam density.

Volatile liquids with boiling points less than 110 °C like the aliphatic hydrocarbons (from C_5-C_7) are useful physical foaming agents. They undergo a phase change during the foaming process. They must be odourless, non-toxic, non-corrosive and non-flammable and have a low vapour thermal stability in the gaseous state and low permeability through the polymer and low global warming potential (GWP). Other requisites include thermal and chemical stability and in some special cases appropriate solubility [12-14]. Since the efficiency of the liquid foaming agents is directly related to the ratio of specific volume of liquid, products with high specific gravity combined with low molecular mass are most effective.

Halogenated aliphatic hydrocarbons possess such characteristics including a very low thermal conductivity, and therefore are ideal physical foaming agents. However, in the mid 1980s it became apparent that further increases in chlorofluorocarbon (CFC) concentrations in the upper atmosphere would lead to long-term damage to the ozone layer. International recognition by scientists and political leaders culminated in the signing of the Montreal Protocol in 1987. This first international protocol addresses the global impact of CFC and outlines a timetable for worldwide reduction of CFC consumption [15].

Recent measurements of the atmospheric chlorine content indicate that the equivalent effective chlorine content in the northern troposphere has been decreasing. This demonstrates that the phaseout of CFC has achieved a very positive environmental impact. In the rigid foam applications, the alternative foaming agents are hydrochlorofluorocarbons (HCFC) with low ozone depletion potential (ODP), and hydrofluorocarbons (HFC) and hydrocarbons with zero ODP. In the USA, the phaseout of CFC-11 in rigid PU applications was made possible with use of HCFC-14b, which offers excellent thermal insulation and fire performances, especially compared to hydrocarbons. In the transitional period following the 1995 restrictions of ODP, HCFC-141b and HCFC-142b, compounds with somewhat similar insulating potentials might be used. But the international agreements ultimately require the use of zero-ODP foaming agents in these applications, (e.g., CO_2, cyclopentanes, and certain HFC). The development of the next generation (zero ODP) foaming agents has been underway for several years [16-19].

7.1.1.2 Chemical Foaming Agents

These are mineral or organic chemicals, usually solids, able to decompose at certain temperatures and to liberate large amounts of gas. Most of them in well-defined temperature intervals liberate in addition to nitrogen, other condensable gases such as CO_2, CO and hydrogen. The residue of the decomposition process becomes part of the matrix and should not affect any of the valuable properties of the polymer. Mineral foaming agents, mostly salts or weak acids can release gas either by thermal dissociation or in the presence of promoters by chemical decomposition. The most important of these agents are ammonium bicarbonate (decomposition temperature 60 °C), which doesn't leave residue during decomposition, sodium bicarbonate (decomposition temperature interval 100-140 °C), and sodium borohydride ($NaBH_4$; decomposition temperature 300 °C). In some case water can also be used as a foaming agent [20, 21].

Organic chemicals able to release nitrogen as the main component of the liberated gas are the most important, their decomposition usually occurs in narrow temperature ranges, and it is an irreversible exothermic reaction independent of external pressure.

Organic foaming agents have some important advantages such as:

- The reaction which liberates the gas is irreversible.
- Some have the maximum gas liberation temperature close to the flow temperature range of the polymer matrix.
- They can be mixed uniformly with the necessary additives.

The disadvantages of organic foaming agents consist of their high cost and in some cases in their toxicity. The non-gaseous products of their thermal decomposition must be taken into account because they can plasticise the polymer, thus decreasing its stability. Most of the known organic foaming agents fall into one of the following classes [22, 23]: azo and diazo compounds, *N*-nitroso compounds, sulfonyl-hydrazides, azides, triazines, triazols and tetrazoles, sulfonyl semicarbazides, urea derivatives, guanidine derivatives, esters. Almost all of these functional organic foaming agents are represented among the commercial products.

7.1.2 Foam Manufacturing Technologies

The foaming mechanism that causes the development of bubbles and the process of formation of the cellular structure can be classified as mechanical, physical or chemical. In the mechanical foaming, the bubbles are created by using an agitator to stir a gas into the mixture of matrix components, or by using high pressure to force the gas into the melted polymer. Latex foam rubber is made by mechanically induced frothing of a latex or liquid elastomer, followed by crosslinking of the polymer in the expanded state. In the physical process, heat produces a low boiling liquid which evaporates, thus forming the bubbles. In chemical foaming, the blowing agent reacts under the influence of heat, releasing gases, which form the voids in the melted polymer beads obtained through suspension polymerisation [24].

Foaming processes lead to products with different shape such as: blocks, boards, sheets, slabs, moulded items and extruded profiles. Some polymer foams can be sprayed onto substrates to form coatings, foamed in place between walls, (i.e., poured into the empty space in liquid form and allowed to foam), or used as a core in more complex structures like panels for the construction industry. Conventional technologies such as extrusion, injection moulding or simple expansion of polymer beads in moulds in the presence of a foaming agent are frequently used [25, 26]. Once the polymer has been expanded, the cellular structure must be stabilised through physical or chemical stabilisation, otherwise it would collapse. If the macromolecular compound is a thermoplastic, expansion is carried out above its T_g or melting point (T_m) and then immediately cooled below the T_m. This is physical stabilisation. Chemical stabilisation requires expansion cooling process, a crosslinking reaction following the expansion. Thermoplastic foams like those made of PS or PVC are usually stabilised simply by cooling. Such polymer-foaming agent mixtures are often extruded and expansion and simultaneous cooling occur as the system is extruded. Crosslinking occurs in the case of the formation of PU, epoxy and silicone foams [26].

The manufacturing of polymer foams can take place by many techniques [11, 27, 28], such as: continuous production of slabstock foams, compression moulding, injection

moulding of expandable beads or pellets, reaction injection moulding (RIM), extrusion, lamination (board production), foaming in place, spraying, vacuum forming. The underlayer of floor coverings are usually produced by mechanical foaming, i.e., the blowing of air through a plastisol during processing [29].

7.1.3 Thermoplastic Foams

The most used commercial thermoplastic foams are made of PS, PVC, polyethylene (PE), polypropylene (PP), ABS and cellulose acetate. Among these, the construction industry uses mostly the first two.

7.1.3.1 PS Foam

PS foams are generally rigid, closed cell and manufactured in densities ranging between 16 and 180 kg/m^3: most are in the 16-80 kg/m^3 density range. Low density PS foams used in the construction industry exist in the form of expanded or extruded products. The first type is produced from expandable PS beads (obtained through suspension polymerisation), by using hydrocarbons, halocarbons or a mixture of both as foaming agents. Confined in a mould and subjected to heat, the pre-expanded beads can produce a smooth-skinned closed cell foam of controlled density, registering every detail of an intricate mould. To minimise the formation of a density gradient and to ensure uniform expansion throughout the moulded product, expandable PS beads are pre-expanded to the approximate required density by control of time and temperature, since the process of moulding does not increase the density [30].

To produce extruded PS foam, a molten PS-based compound containing a foaming agent is processed at a certain temperature range and pressure through a slit orifice to atmospheric pressure - the mass expands to about 40 times its pre-extrusion volume. It is produced in board form with a continuous surface skin or in large billets (boards) that can be cut into standard board or fabricated into desired shapes. The extruded foam has a more regular structure than the moulded one, better strength and higher water resistance [10].

Table 7.2 shows some physical properties of commercial PS foams.

PS foams resist moisture well, but deteriorate when exposed to direct sunlight for long periods of time as shown by a characteristic yellowing. The colour change is accompanied by marked changes in the average molecular weight (MW) and in tensile strength [32]. Multiple coats of water dispersed exterior paints, cement plaster, latex modified plasters and asphaltic emulsions can provide protection against physical damage. Mechanical

Table 7.2 Physical properties of commercial PS foams [31]		
Property	**Extruded**	**Expanded**
Density, kg/m^3	35	80
Compressive strength, kPa, at 10%	310	586-896
Tensile strength, kPa	517	1.020-1.186
Thermal conductivity, W/m.K	0.030	0.035
Water absorption, vol%	0.02	–
Moisture vapour transmission, g/m.s GPa	35	23-35
Reproduced with permission from D. Klempner and K.C. Frisch, Polymer Foams, published by C. Hanser Verlag, 1991		

properties are also affected by temperatures close to the T_g, which means that different grades of PS foam are affected by temperature in the range of 71-77 °C. For short exposures to temperatures up to 100 °C, PS foam is resistant – it decomposes at approximately 300 °C.

In the vicinity of a flame, the foam fuses and burns like plastic PS with a luminous yellow, sooty flame and a sweetish odour. It burns until the ignition source is removed. The introduction of flame retardant makes PS foams less flammable. Compared with PS plastic which is processed at temperatures up to 260 °C, the manufacture of expanded PS is carried out at around 120 °C and the extruded PS foam is produced at about 260 °C. These conditions enable the less thermally stable aliphatic and cycloaliphatic bromine flame retardants to be used [33].

Experimental data [34] confirm that the thermal performance of the extruded PS foam is very stable. Although seasonal variation of this performance was detected (probably caused by migration of moisture to and from the adjacent wood products), the average field performance remains constant.

In the construction industry PS foams are used as: perimeter insulation, roof deck insulation, and masonry wall insulation. The requirements for perimeter insulation, applied below ground level along the edges of a concrete foundation, are relatively high thermal resistance for a given thickness, good moisture resistance and a good compressive strength. The product for roof insulation should have good dimensional stability and high flexural and compressive strength, and should preferably be of a fire retardant grade. It must also be protected from overheating and melting when hot asphalt or coal tar pitch is used to adhere the foam to the deck. Placing foam boards between the masonry of a building's exterior and interior walls or by bonding the foam directly to the wall can readily insulate the buildings.

Due to its relatively good thermal resistance, stability to water and water vapour, ease of fabrication and ease of bonding to other construction materials such as metals, wood, concrete or plaster faces, PS foams are widely used as a core for sandwich panels. The most important drawback for this application is that it undergoes heat distortion.

7.1.3.2 PVC Foam

PVC foams differ from most other foams in having a broad range of characteristics because they can be formulated in various ways, with different foaming agents, and using different foaming technologies.

The foam for the construction industry is made mainly without plasticiser. Such an additive is introduced in the manufacturing of flexible or semi-flexible foams.

The greatest interest in rigid PVC foam is in applications where low flammability requirements prevail. Most PVC foam products are made with chemical foaming agents such as azobisformamide in amounts of 1 to 2 wt% [35]. They have an almost completely closed cell structure and therefore low water absorption.

A single-screw extruder or a twin-screw extruder is used for the manufacturing of PVC rigid foam. This type of foam is widely used as the core of some sandwich and multilayer panels. The flexible one is used as the foam layer in coated fabric flooring. Its low vapour transmission is an advantage when condensation might be a problem.

Due to the fact that foaming characteristics deteriorate with increasing MW, types of PVC with a MW of fewer than 65,000 are preferred. If high demands are made on the physical-mechanical properties of the semi-finished foam products, then types of PVC with high a MW are used despite their inferior foaming characteristics. These can be compensated for by using a larger amount of foaming additive [36].

Some of the best advantages of PVC rigid foam are: low volume cost, good mechanical characteristics (high tensile, compressive and shear strength), good chemical and weather stability, low thermal conductivity, low water permeability, resistance to termites and bacterial growth, good fire stability and they do not crumble under impact or vibration.

Microcellular PVC foams with a relative density (density divided by the density of unfoamed polymer) ranging from 0.15 to 0.94 and with a very homogeneous cell distribution and cell densities ranging from 10^7 to 10^9 cells/cm^3 have been produced [37].

It is possible to produce rigid PVC closed cell foam with exceptional strength, through a crosslinking reaction with maleic anhydride, isocyanate and a catalyst [30].

With regard to the mechanical properties, the rigid PVC foam with a low density of 40 kg/m^3 has a compressive and shear strength of about 0.34 MN/m^2, a tensile strength of 0.48 MN/m^2 and a flexural strength of 0.38 MN/m^2.

In the construction industry, PVC foam is used for wall panelling, as a flooring material, insulation of metallic pipes, shutter boxes, wall partitions, door panels, and window boxes [36]. It is also used in sandwich panels to increase their stiffness [10].

7.1.4 Thermosetting Foams

In this group of products, foaming takes place at the same time with the chemical reaction (polycondensation) between the initial starting materials in view to produce the polymer. The most common are made of PU, PIR, PF, UF, EP, and silicone polymers. The most versatile and most used in the construction industry are the foams based on PU and more recently on PIR.

7.1.4.1 PU and PIR Foams

PU foam is available in flexible or rigid forms, closed and open cell. Its characteristics depend on: the nature of the starting components, the type of the foaming agent and the technology used. The starting components are polyisocyanates (prepolymers) and polyols (polyesters or more usually polyethers). The polycondensation takes place in the presence of some additives such as a selected catalyst, a stabiliser, foaming agent and flame retardant. The heat released during the process is used to evaporate the resulting liquid physical foaming agent [38]. The use of water generated CO_2 as a foaming agent, is well known and produces a more stable foam, through higher thermal conductivity [39].

Though closed cell rigid PU foams are excellent thermal insulators, they suffer from the drawback of unsatisfactory fire resistance even in the presence of phosphorus, and halogen-based flame retardants. From the flammability point of view, PIR, which are also based on isocyanates have greater flame resistance than PU. PIR withstand service temperature up to 149 °C compared with 93 °C for PU [35].

PIR foams are produced by using standard PU foaming equipment. Unmodified PIR foams have a highly crosslinked structure, and therefore are extremely brittle. What did prove successful was to lower the crosslinking density of the foams by adding modifiers, which led to, modified polyisocyanurate foams such as [40]: urethane-modified PIR foam, amide-modified PIR foam, imide-modified PIR foam, carbodiimide-modified PIR foam and oxazolidone-modified PIR foam.

The most used technologies for producing rigid PU foams include foaming in place, spraying and continuous slabbing. Foaming in place is convenient especially for filling irregular voids or cavities. It requires relatively portable equipment and, in many cases, is conducted outdoors or under poorly controlled conditions. The use of CFC provides rapid expansion or frothing. The resulting product is less uniform in quality than those formed in more controlled, in-plant operations [39]. The spraying technique permits thin layers of PU foam to be built up on large, uneven surface areas and additional layers can be applied. It is an effective way of insulating and sealing commercial and residential buildings. In all cases, the exposed, usually rough surface of sprayed foam must be protected by fire resistant materials [10, 39]. The slab (block) or sheet produced by slabbing technology can be cut after curing or formed to a specific shape and size. Coated sheets are widely used for construction applications such as roofing or facing for frame construction [35].

Chemically, rigid PU foam can be considered the most complex of polymer foams because of its high number of additives. It is the most widely used and it is the most expensive. It offers a series of advantages as a thermal insulator, such as: low thermal conductivity, light weight, high strength, extreme versatility with which it can be formulated to meet a wide range of requirements, ability to form a strong adhesive bond with many materials, low water permeability, stability up to 90 °C, ability to be foamed *in situ* to fill complex shaped cavities. More recently introduced PIR foams, closely related to the PU foams, have higher thermal stability and inherently better flammability characteristics. Both PU and PIR rigid foams are usually anisotropic in their strength characteristics [41].

Rigid PU and PIR foams as normally used for building thermal insulation have a density of 30-35 kg/m^3. Thus the product is about 97% gas, which is contained in non-interconnecting cells with diameters in the range of 0.2-1.0 mm. The physical properties depend on the interaction and separate contributions of the gaseous and solid phases. Strength depends on the polymeric phase, thermal conductivity depends on the gas phase and dimensional stability depends on both phases. The most important parameters affecting long-term dimensional stability can be brought together in four categories, which are: matrix strength, cell gas pressure, processing and plasticisation [42].

Dimensional stability in the case of closed cell foams is dependent on the ability of the foam to resist atmospheric pressure. Changes in the internal cell pressure are due to the fact that the initial gas in the cells does not diffuse out quickly. The foam, to be stable, must resist the differential pressure.

Values of thermal conductivity (K factor) depend on density, closed cell content, composition of the gas. Cell size and orientation also affect the K factor, which decreases with the decrease of temperature independent on the nature of foaming agent [39].

The time at which cell gas minimum pressure is obtained is dependent upon foam structure, i.e., number of cells, thickness of the cell membranes, foam size, ageing temperature and facing material [42].

The two largest markets for PU and PIR rigid foams are in building thermal insulation, where they are supplied as sheets produced on a laminator and applied for roofing, sheathing, and facing panels. The sprayed foam is used for complex or uneven surfaces. The low thermal conductivity of rigid PU foam allows thin wall design and more efficient use of space. PIR rigid foams are superior to PU and PS foams in terms of low rate of heat release (RHR) and low rate of smoke release, probably due to its higher decomposition temperature.

7.1.4.2 Phenolic (PF) Foam

The early technique for PF manufacturing was based on the expansion of novolac-hexamethylenetetramine (HMTA) mixtures. Now, the manufacturing is based on acid catalysed process of a resole type PF with added foaming agent and surfactant [43].

PF foam has good chemical and thermal stability, high resistance to water transmission and water uptake, good dimensional stability, high strength to weight ratio, high insulation value per cm, and good flammability characteristics. However, due to its high open cell content it has relatively low thermal resistance. The cell sizes of closed cell PF foams are about half the size of typical PU and PIR foams. Thus there are more cell walls per cm^3, which results in greater retention of insulation efficiency. Cell sizes vary in the range 0.08-0.2 mm [44]. Thermal insulation efficiency can be improved by the application of a suitable skin material.

PF foam technology has progressed in recent years so that slabstock and laminated boards can now be produced using continuous technologies. PF cannot match the versatility of foam/facing combinations developed by PU and PIR, but it offers to the construction industry a useful combination of physical, mechanical and fire properties.

The resole closed cell foam can be classified as: high closed cell content, low thermal conductivity, high fire resistance, and high closed cell content, low thermal conductivity and low fire resistance. Both these types have a density of 40 kg/cm^3, a thermal conductivity of 0.02 kcal/m.h.°C, a closed cell content of 90%, a water absorption of 0.5 g/100 cm^2, but the limited oxygen index (LOI) is 50 for the first type and only 33 for the second one. Compressive strength varies between 1.6 and 2.0 kg/cm^2 and the tensile strength is 1.1 kg/cm^2 [45].

While the fire characteristics are attractive to users, manufacturers have to overcome some weak points of this foam such as: low productivity, high friability and low yield rate in materials [10, 45].

7.1.4.2 Urea-Formaldehyde (UF) Foam

This foam is produced by polycondensation of urea with formaldehyde in an alkaline medium, the reaction proceeding further under weakly acidic conditions. Because factory made foam slabs are easily damaged during transportation and occupy excessive and uneconomical shipping volume, UF foams are produced on site by spraying from portable foaming equipment, containing the resin (prepolymer) stock, water solution and a hardener-surfactant solution. The system also contains a catalyst and more often than not a mixture of foaming agents. A good foam sets within the first minute when it can be sliced if need be. It hardens fully within one day. The residual water vapourises from the cured foam. If the drying is too quick, it tends to warp, shrink or crack.

Home insulating foam in closed spaces, retains moisture on occasion for several years, mainly in cold climates. UF foam, having a density of 10-14 kg/m^3, is the lightest of the polymeric insulating materials. It is white, has no mechanical strength even in compression, and does not support combustion and it is very friable. Commercial products have a closed cell content of about 80%. UF foams have a thermal conductivity of 0.022-0.029 W/m.K. Its maximum service temperature is very low, around 49 °C. If not formulated properly UF foams lose their insulation efficiency. Since they are water-absorbing, they lose this characteristic at high humidity [30].

A drastic decline in the production and use of UF foam undoubtedly resulted from the health danger from gaseous formaldehyde released by the foam due to the incorrect ratio of components (excess of formaldehyde), high humidity, excess of foaming agent. As a result it was banned in some countries and in the USA, the Consumer Products Safety Commission (CPCS), ruled against its use [30, 46-48]. Gaseous formaldehyde is an irritant to the eyes, nose and throat, and is classified as 'suspected human carcinogen' which should be controlled in workplaces to gas concentrations below 1 ppm. In Australia this concentration should not exceed 0.1 ppm in dwellings and schools [49-54]. To reduce formaldehyde emission post-manufactured board treatments were proposed such as [55]:

- Application of scavengers as solids or aqueous solutions based on ammonia compounds
- Exposure to scavengers as gases (ammonium, sulfur dioxide)
- Application of coatings
- Lamination with barrier materials, like polymer films, metallic films, impregnated paper.

7.1.4.3 Epoxy (EP) Foam

EP foams are among the hardest and stiffest foams because they are highly crosslinked. The processing and final physical properties depend on their chemical composition and degree of cure (crosslinking) [55]. Curing is realised using primary amines, anhydrides or polyphenols. The density can be adjusted by the amount of foaming agent. To achieve full strength, the foam should be postcured for several hours. The densities of EP foams range from 32 to 600 kg/m^3. The low-density foams are serviceable up to 82 °C. At a density of 140 kg/m^3 the compressive strength is around 1 MPa and tensile strength 0.7 MPa [30].

7.1.4.4 Silicone Foam

Thermosetting silicone foams are available in densities from about 48 to 240 kg/m^3. They can be moulded or sprayed in place. Board stocks are also available. Fillers and crosslinking agents improve their physical strength and toughness. They possess good low and high temperature stability.

7.1.5 Special Foams

7.1.5.1 Syntactic Foams

These foams can be defined as composites consisting of hollow microspheres and a polymeric matrix. This one is made of a thermosetting (PU, PIR, PF, EP, silicone or unsaturated polyester) or of a thermoplastic (PE, PP, PVC, PS, polyimide) [56]. The microspheres can be made of silica, glass, carbon, ceramics or polymers such as PS, PE, PP, polyamide (PA), polymethyl methacrylate (PMMA), divinyl benzene (DVB)-maleic anhydride, and so on [56-58]. The diameter of the tiny hollow spheres is 300 mm or less [35]. They contain an inert gas such as nitrogen or a CFC. The properties of these syntactic foams depend on: matrix type, microsphere type (and the contained gas), ratio matrix to microspheres, curing process, production technology. Syntactic foams can be made in combination with the conventional ones. Such a complex composite can be formulated into a mouldable mass then shaped or pressed into cavities.

Epoxy syntactic foams are the best-known representatives of this type of special foam. The main disadvantage of such a matrix is its high viscosity at ambient temperature, but the adding of diluents can circumvent this [20].

7.1.5.2 Structural Foam

The term 'structural foam' designates components possessing skins and cellular cores, similar to structural sandwich panels. For structural proposes, they have favourable strength and stiffness-to-weight ratios, because of their sandwich type configuration. Frequently, they can provide enhanced structural performance at reduced cost of materials and for this reason they are replacing structural parts, mainly those made of wood, metals or solid plastics. High-impact PS (HIPS) is the most widely used structural foam, followed by PP, high-density polyethylene (HDPE), and PVC. The sandwich type structure of PU with a smooth integral skin produced by RIM provides a high degree of stiffness and excellent thermal and acoustical properties [31].

7.1.5.3 Microcellular Polymers

Microcellular polymers are closed cell thermoplastics produced by gas nucleation. They have a high number of very small cells with a diameter of 10 μm, and bubble densities in excess of 100 million per cm^3. First produced in the early 1980s with the objective of reducing the amount of polymer used in mass produced items, these novel materials have the potential to revolutionise the way thermoplastic polymers are used today. PVC, PS, polycarbonate (PC), polyethylene terephthalate (PET) and not only these polymers can be applied for such kinds of products. As no harmful chemicals are used in the microcellular technology, it is likely that these new products will replace many types of foam now produced by processes that damage the environment [59].

7.1.5.4 Acoustic Insulation Foams

The acoustic characteristics of polymers are altered in a cellular structure. Sound transmission changes only slightly, because it depends mainly upon the barrier density, in this case the polymer phase. Therefore polymeric foams are poor materials for reducing the transmission of the sounds. They are however, effective in absorbing sound waves of certain frequencies.

In open cell structures the gas is air and for this reason they have a higher absorptive capacity of moisture, a higher gas and vapour permeability, less effective insulation capabilities for either heat or electricity, and a better ability to absorb and dampen sound. For any polymer composite, the proportion of open gas structural elements increases as the density of the foamed plastic decreases, because an increase in cell size means a decrease in the thickness of cell walls and ribs [60]. The combination of other advantageous physical properties with fair acoustic characteristics has led to the use of plastic foams in sound proofing [31].

Many open cell foams such as PU, PIR, PS and integral foams based on polyphenylene oxide are used in construction for acoustic insulation [61-63]. UF and PF foam are used for interior sound absorbing floors [31].

7.1.5.5 Electrical Insulation Foams

Organic polymers are inherently electrical insulators, as a consequence of their microstructures of covalently bonded discrete molecules, a characteristic which has long been exploited for restricting access and affording environmental protection to metallic conductors carrying electrical power. Plastics are used also to restrain high electrical fields. The expansion of plastics industry that occurred in the 1940s led to the replacement of rubber insulation with PVC.

Unlike the common plastics, conductive polymers offer a unique combination of properties that make them attractive alternatives to traditional conducting materials. Polymers, which are conducting rather than insulating, offer properties providing exciting possibilities for new applications [64].

The substitution of a gas for part of the polymeric matrix usually changes the electrical properties. The dielectric constant, dissipation factor, and dielectric strength are lowered roughly proportionally to the amount of gas in the foam. The lower the density of the cellular plastic, the lower the dielectric constant and the better the insulation. Because the dielectric strength is also reduced, the insulation is susceptible to breakdown from voltage surges from lightning and short circuits. Polyolefin foams are preferred for low frequency electrical insulation - PVC, PS foams, silicone and fluoropolymer foams are also used [31, 65, 66].

7.2 Ageing

The rate of deterioration of materials depends on their nature, for the hardest rocks, the time scale stretches to millions of years, whereas for some organic polymers, major modifications can be induced by exposure of only a few days. Ageing is often used somewhat interchangeably with the term degradation.

The ageing process of polymers occurs in a wide variety of environments and service conditions, and very often limits the service lifetime [67]. Ageing is the adverse or detrimental change in a desired physical or chemical property. This process is primarily caused by the climatic stresses of sunlight, pollutants, temperature and water (dew, humidity, rain, snow). To serve satisfactorily, polymers, like most materials, must meet

the more stringent requirements of general use in terms of sustaining their function with a minimum of change in properties. They have to be maintained in a wide range of situations including use under rigorous weather, that is the case for some plastics used in construction [68, 69].

Polymer degradation can be caused by chemical factors (oxidation-degradation, hydrolysis), heat (thermal-degradation), light (photo-degradation), ionising radiation (radio-degradation), mechanical action (mechanical-degradation), or by fungi, bacteria, yeast, algae, and their enzymes (biodegradation).

In principle, there are a few ways to control the ageing process, such as through the use of stabilisers, by avoiding unnecessary thermal exposure, and by excluding oxygen and water as much as possible [70]. Stabilisation is the procedure of slowing down the rate of degradation. Free radical stabilisation techniques commonly used include: UV screeners, UV absorbers, free-radical scavangers, excited-state quenchers and peroxide decomposers [71, 72]. Because of synergistic action of radiation and oxygen, antioxidants as well as UV absorbers are generally added to construction plastics designed for exterior use.

The profound knowledge of polymer ageing is useful to develop stable polymer materials. It is well known that ageing affects not only the microstructure but also the morphology of polymers [73].

The deleterious effects of weathering on construction polymers used outside buildings have been ascribed to a complex set of processes in which the combined action of UV light and oxygen are predominant [72, 74-80]. Biodegradation of polymers is due first to the attack of its additives (plasticisers, antioxidants, processing aids, stabilisers, dyes and extenders) by microorganisms such as bacteria and fungi via enzymic action. These additives are more susceptible to biological attack than the polymer and only after their attack degradation does take place [81-84]. In order for biodegradation to occur, some prerequisites must be satisfied [82]:

- The presence of fungi, bacteria, actinomycetes, and so on
- The presence of oxygen, moisture and mineral nutrients
- A temperature in the range of 20-60 °C depending on the type of microorganism
- A pH in the range of 5 to 8.

With today's accelerated weathering equipment, it is possible to generate reliable weatherability information in a matter of days or weeks [85].

Polymer composites in outdoor applications are susceptible to photoinitiated oxidation leading to surface degradation and are also sensitive to moisture-induced damage, alkaline

solutions or saline solutions [86, 87]. The durability of polymer composites in environments such as replacements for steel reinforcing bars in concrete (a highly alkaline environment), off-shore and marine structures is one of the primary issues limiting their acceptance in infrastructure applications [86].

Physical ageing effects are operative for all polymer composites (based on thermoplastics, thermosets) representing semicrystalline, amorphous and highly filled amorphous matrices. Time/ageing-time and time/temperature superposition are found to be valid procedures for short-term creep behaviour; they cannot be applied to long-term creep behaviour [88]. The ageing in the form of creep performance has been analysed for a large series of polymer composites. Physical ageing causes a significant reduction in the creep of such systems and its influence is comparable in magnitude to that of temperature [89].

A study [90] shows that in the case of glass fibre/polymer composites, the environmental attack by moisture for example, can degrade the strength of the fibre, plasticises the matrix, swells or microcracks the matrix, and degrades the fibre/matrix interface by either chemical or mechanical attack. The relative rates of these degradation processes are a function of the type of the polymer, temperature, exposure time, degree of stress (cyclic, static), type of the fibre, its coating and the nature of the coupling agent.

The ageing of polymer foams is due to a more complex mechanism because it can be produced by matrix degradation, by changes in gas composition or because of both. During ageing the foam structure and the main properties such as thermal conductivity in the case of thermal insulation, are modified.

After manufacturing, the composition of cell gas in many cases is based on a CFC (Freon) and CO_2. For example the PU cell membranes are permeable to the gases present in the foam, though to a different extent, as measured by the diffusion coefficients. The CFC having a higher molecular weight diffuses much more slowly than nitrogen, oxygen water or carbon dioxide molecules. A minimum of cell gas pressure *versus* time is obtained because carbon dioxide diffuses out at a much faster rate than other gases. The time at which this cell gas minimum pressure is obtained is dependent upon foam structure, i.e., number of cells, thickness of the cell membranes, foam sample size, ageing temperature and facing material [42]. The mass transport of each gas species occurs by three modes: permeation through the cell walls, diffusion across the cells interior and infusion and effusion through breaks and holes of the cell walls [39]. The net effect of the dilution of low thermal conductivity CFC with gases with higher thermal conductivity (oxygen, nitrogen, water vapour) is a gradual increase in the K value of the foam. The change in this characteristic is due rather to the influx of air than to the efflux of CFC, since the change in CFC content is small compared to the increase in the concentration of nitrogen and oxygen in the cells (**Figure 7.1**).

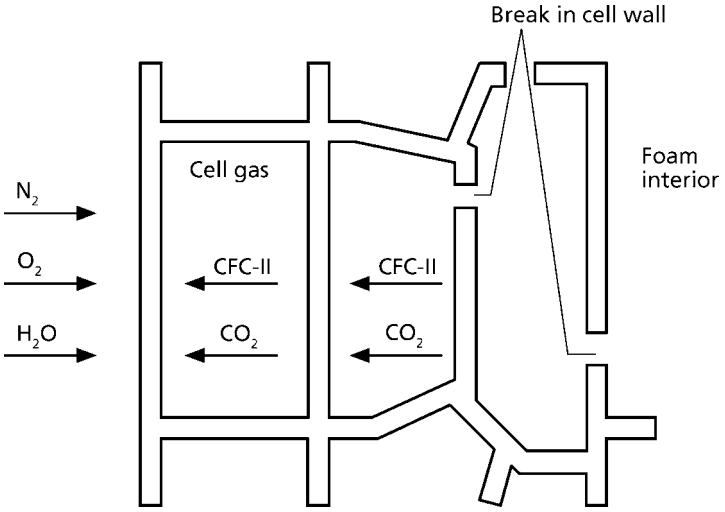

Figure 7.1 Diffusion of nitrogen and oxygen

In the ageing process the gas composition in the cells will change gradually towards the equilibrium, i.e., until the composition in the cells is equal to the surrounding air.

Foam ageing depends strongly upon its application and the facer material. If faced with diffusion-tight barriers, the low initial thermal conductivity remains unchanged [38]. A key factor tending to diminish the effectiveness of facing on foam slabs is the lack of good adhesion of the faces to the rigid foam substrate. This lack of good adhesion occurs frequently with commercial products. Many detailed laboratory studies have been carried out to determine the effects of long-term ageing on the thermal conductivity of the polymer foams [42-44, 91-95].

PU foam withstands, without difficulty, both water and a wide range of petroleum products, but has poor resistance to mineral acids, and moderate resistance to a wide range of organic solvents. Recently it was pointed out that the changes in physical and mechanical characteristics (thermal conductivity, open pores content, strength) during long-term ageing of PU foams are explained by influence of thermal and thermal-oxidative degradation of the polymeric matrix [96].

7.3 Electrostaticity

The electrical charge capacity of an item depends on the condition of its surface, on the dielectric constant, the surface resistivity, and the relative humidity of the surrounding

atmosphere. While the charge capacity is inversely proportional to the dielectric constant and relative humidity, it is directly proportional to surface resistivity. The sign of the electrical charge is invariably from the material with the higher to the one with the lower dielectric constant. An electrostatic discharge event can produce sufficient energy to ignite some materials, resulting in fire or explosion.

Due to their composition, most plastics are powerful insulators, a property that makes them indispensable materials for high frequency equipment (radar). An associated drawback of the electrical insulation characteristic is the accumulation of static electricity, which is not discharged fast enough due to the low surface conductivity of most plastics, a difference between plastics and metals. The material, which gains electrons, becomes negatively charged, while the material that loses electrons acquires a positive charge [97]. In an explosive environment, this sudden transfer of charge may be energetic enough to serve as an ignition source [98-100].

There are three basic routes to modify the static discharge behaviour of plastics used in building or other applications:

- Incorporating electro-conductive fillers into the plastic compound
- Incorporating migrating, internal antistatic agents
- Treating the finished product with a coating (painting) of an external antistatic agent [97, 101, 102].

Internal antistatic agents are of interfacially active character, and via migration accumulate on the surface of the plastic product. Their molecules posses hydrophobic and hydrophilic groups; the former confer a certain compatibility with the polymer and the hydrophilic groups take care of the binding and exchange of water on the surface. They are anionic, cationic or nonionic compounds [97]. External agents are applied to the surface of the plastic material in the form of aqueous or alcoholic solutions.

Besides the charge control agents (also called charge additives, charge assistants or charge direct agents), there is a class of compounds able to stabilise triboelectric charge. They are called charge stabilisers. In comparison with charge control agents, they show lower charging magnitude but higher long-term stability [103].

Many recent studies deal with flooring materials [104-106], elctrostatically actuated window [107], electrostatic testing of materials [108], charge transfer metal/polymer [109], a new unsaturated antistatic polymer able to be used for a storehouse of inflammable and explosive materials [110].

7.4 Fire Safety

Most national fire safety strategies are based on prescriptive approaches that have been developed historically to meet fire safety needs, often in the wake of major fire disasters. Building regulations of most countries have codes that can be stated in very general terms, as seeking to insure that [111]:

- The structure remains stable for the required period (fire resistance),
- The fire is contained within defined compartments by the appropriate fire separating elements (fire resistance),
- Internal spread of fire (and smoke and toxic gases) is restricted within the building (reaction-to-fire and fire resistance),
- Spread of fire from one building to another is limited (reaction-to-fire and fire resistance),
- Adequate means of escape are provided (reaction-to-fire and fire resistance), and
- Access and provision are maintained for firefighting and rescue.

Fire is a continuous threat to life and property. The human cost is financially incalculable.

The demand of better and safer engineering materials has lead to a rapid proliferation of high performance polymers in the building construction and other industries. Polymers used in building for thermal and acoustic insulation, panels, carpets, frames for door or windows, floor tiles, cable insulation, paints, wallpaper, etc., are exposed to fire. Most being organic polymers, are combustible, decompose thermally, and decomposition products burn. In the case of polymers used in buildings, fire safety combines: thermal decomposition, ignition, flame spread, heat release, smoke obscuration, ignition, and other characteristics [112].

Our environment is largely one of organic polymers and these materials burn, whether natural like wool or wood, or synthetic. With improved building design, home fire deaths decreased in USA about one-third between 1980 and 2000 from 5200 to 3420; civilian fire deaths in 2000 were 38% lower than in 1980. Plenty of factors were involved, including much wider use of smoke detectors and greater public awareness about fire prevention. Even though the rate of home fires has fallen, it remains twice that of most European countries and the number of deaths by fires is still about the same.

Polymers are degraded by intense heat to yield micromolecules in gas or liquid state, which are often flammable and thus provide fuel in a fire situation. These combustion

products can be determined by gas chromatography, nuclear magnetic resonance (NMR) spectroscopy, infrared (IR) spectroscopy, mass spectroscopy, and others. Additivity of molar groups appears to be a viable method for calculating the heat release capacity of plastics from their chemical composition based on the high correlation between measured and calculated values [113]. Presence or absence of a flame or spark gives the pilot or auto ignition temperature, which varies from one polymer to another. For example, PU foam used for thermal insulation has a pilot ignition temperature of 310 °C and an auto ignition one of 416 °C, compared with the PS foam where the pilot ignition temperature is 316 °C and the auto ignition is 491 °C.

The continuous rapid growth of applications of polymers in construction and other areas coupled with the rising proportion of deaths attributed to toxic gases/smoke, have led to widespread concerns over the toxicity of burning polymers and their possible contribution to the trend.

Nonflammable polymers, by definition, possess significant fire-resistant properties because of their chemical structure or due to some additives. All thermally stable plastics belong to the broad nonflammable plastic group, but a number of them within this group possess performance characteristics that are different. Halogenated polymers such as PVC, fluorinated polymers or those, which contain flame retardant, are classed as fire resistant. In fact, every plastic can be improved by the addition of fireproofing agents [114-118].

Combustibles must be produced before the ignition of polymers to flame. By heating a plastic it eventually reaches a temperature at which the weakest bonds start to break, and little change occurs such as discoloration. At higher temperature pyrolysis: 'an irreversible chemical decomposition due to an increased temperature without oxidation' plays the main role in the production of combustible gases in the burning of plastics [119].

The process starts at ignition and continues after it to the complete consumption of the material if the heat fed back from flames to the plastic is sufficient to keep its rate of degradation above the minimum value for feeding the flame itself. Otherwise, the cyclic combustion process stops and the flame extinguishes.

The essential requirements for fire are: heat, oxygen and fuel [120], as illustrated in **Figure 7.2**. Once combustion has occurred, the course of the fire often accelerates rapidly, passing from ignition initiation through fire propagation to fully developed fire and its decay (**Figure 7.3**) [121].

Plastic characteristics related to their combustion are ignition and flash point, thermal conductivity, specific heat capacity and exothermic heat of combustion. Ignition occurs when a sufficient amount of combustibles (gases or liquids) are produced. The combustion mechanism is complex and involves reactions between radicals resulting during plastic degradation [120].

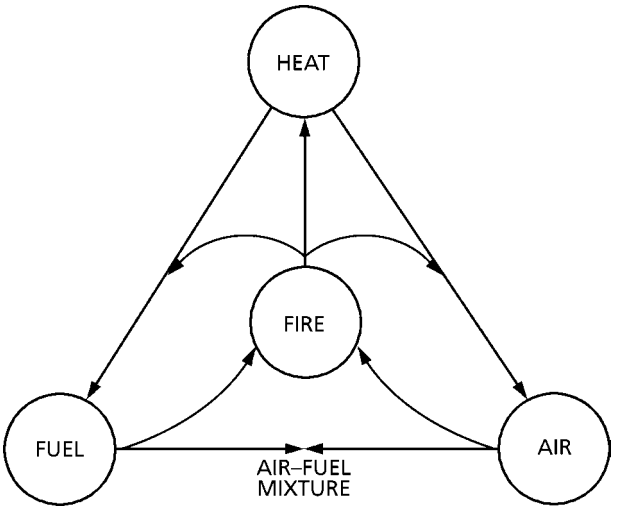

Figure 7.2 The fire triangle [120]
(*Reproduced with permission from A.W. Barley and co-workers, Physics of Plastics, published by C. Hanser Verlag, 1992*)

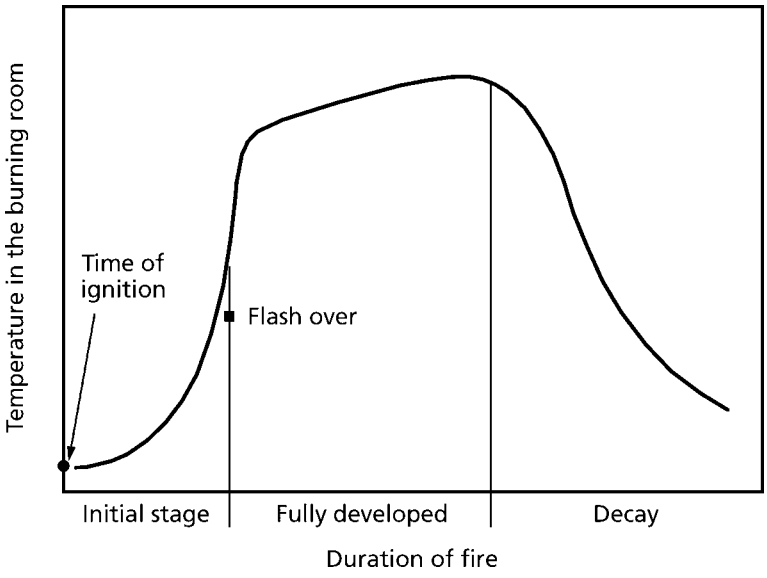

Figure 7.3 Time-temperature profile of large scale fires [121]
(*Reproduced with permission from P.J. Fardell, Toxicity of Plastics and Rubber in Fire, Rapra Review Report No.69, Rapra Technology Ltd, 1993*)

In the early studies of the combustion of organic materials, their reaction to fire was defined by the time to ignition and rate of flame propagation. The experience acquired on causalities, and building damage in fires has led to the consideration of other characteristics of building materials such as: rate of heat release (RHR), optical density, toxicity and corrosiveness of smoke produced on burning. About 800 tests have been developed worldwide to characterise the plastic's reaction to fire. Many such tests have been designed to measure the same characteristics, with however, contradictory results in some cases [122].

Fire resistance has a very special meaning, relating to the ability of an assembly to remain structurally stable in the presence of a fire. It does not mean resistance to ignition or to flame spread. An example is 'self extinguishing' which implies that a product will be safe in the presence of fire. All that is really meant is that if a small flame is applied on to the surface of a sample, than any burning will cease after its removal. It is also thought that once a product has passed a test it is fire safe, and will remain so throughout its working life. None of this is true. No test can guarantee fire safety [123].

Fire testing and classification of building and other materials are based on certain flammability characteristics such as: flame spread, ignition temperature, smoke development, non-combustibility, fire resistance, rate of heat release, oxygen index, etc. Some of them are briefly discussed in the following paragraphs [124-126].

Steiner tunnel tests (ASTM E84) [127] measure the surface flame spread of a material. The specimen is exposed to an ignition source, and the rate at which the flames travel to the end of the specimen is measured. The severity of the exposure and the time a specimen is exposed to the ignition source are the main differences between the tunnel test methods [119]. The data obtained provide a measure of fire hazard, in that flame spread can transmit fire to more flammable materials in the vicinity and thus enlarge a conflagration, even though the transmitting material itself contributes little fuel to the fire.

Tunnel testing provides data on: burning rate or combustion rate, burning extent or distance of flame travel, flame spread factor and flame height. It is a mandatory test for flooring materials and many others. Materials are rated on flame spread classification with red oak as 100:

- Moulded plastics range between 10 and 100
- Polymer composites between 15 and 160

Flash ignition temperature is defined as the lowest initial temperature of air passing around the specimen from which a sufficient amount of combustible gas is evolved to be ignited by the external pilot flame. Self-ignition temperature is defined as the lowest

Table 7.3 Flash and self-ignition temperatures of polymers [33]		
Polymer	**Flash ignition temperature, °C**	**Self ignition temperature, °C**
Douglas fir	260	
PE	341-357	349
PVC	391	454
PS	345-360	488-496
PMMA	280-300	450-462

initial temperature of air passing around the specimen at which, in the absence of an ignition source, the self-heating properties of the specimen lead to ignition, or ignition occurs of itself, as indicated by an explosion, flame or sustained glow.

Table 7.3 presents such data for some common polymers.

Smoke seems to be the biggest killer of people who die in fire, not flames. Smoke produced during the combustion of polymers is a suspension of solid (carbon) particles in a mixture of gaseous combustion products and ambient atmosphere. Depending on the type of polymer and conditions of combustion, such a suspension can consist either of liquid droplets or solid particles, possible with additional condensation of products from the gas phase flame reaction on the surface of these solid particles. The principal hazard of smoke is that it hinders the escape route of occupants and the entry of fire fighters. Smoke can contribute to panic conditions because of its blinding and irritating effects, furthermore, in many cases, smoke reached untenable levels in exit ways before temperature reached untenable values.

The inability of potential victims to escape from a fire, ultimately resulting in fatalities, should be considered in terms of three major factors:

a) smoke - obscuration of vision,

b) heat, and

c) toxicity of fire gases [128].

In the early stages of a fire, smoke doesn't contain a high enough concentration of dangerous gases to be lethal. However, the smoke, by its irritant properties and obscuration of normal visibility immobilises people within the area of the building where they are 'trapped' and may be killed by the lethal toxic gases and heat. In terms of lethality, 70% of the people who die from fires die as a result of the inhalation of toxic gases [129].

The nature of smoke produced during the burning of polymers depends to a large extent on their chemical composition, pyrolysis conditions and oxidation processes.

For example, during the incomplete combustion of PVC, a thick fog, which contains droplets of hydrochloric acid, is produced. In general, this acid is formed from the combustion of chlorine-containing materials, the most notable of which is PVC. Hydrochloric acid is both a potent sensory irritant and a pulmonary irritant, being also corrosive to sensitive tissues such as the eyes [130].

Polymers like polyoxymethylene (POM) and polyethylene terephthalate (PTFE, Teflon), do not form hydrocarbon compounds during combustion and do not exhibit an inclination towards formation of soot. Polyolefins, which form predominantly aliphatic hydrocarbons during pyrolysis, are less inclined to form soot than others like PS, styrene copolymers or ABS, which produce aromatic hydrocarbon [131].

Most of the tests done for smoke characterisation are gravimetric or optical, the latter measures the density of smoke accumulated in an enclosure or density of smoke past specific location [132].

Toxicity of smoke is measured by analytical or biological methods [133], and is defined as the action of some agents upon an unprotected individual, which impairs the vital functions of the human organism.

The nature of smoke particles and its toxic gas emission vary besides the factors already mentioned with the fire temperature. The toxic components of smoke can be: asphyxiants (carbon monoxide, carbon dioxide, hydrogen cyanide) or irritants (hydrochloric acid, aldehydes, organic acids, others). Between 200 and 400 °C, low yields of hydrocarbon species derived from the partial breakdown of polymer macromolecules are observed. Between 400 and 700 °C an extensive breakdown takes place and oxygen from the surrounding atmosphere is incorporated in the combustion products. In such circumstances very irritant species such as aldehydes and organic acids are produced. Above 700 °C organic compounds will be decomposed and some rearrangements with the formation of polycyclic aromatic hydrocarbons (thought to be precursors of carbonaceous smoke) together with hydrogen cyanide (HCN) from polyacrylonitrile (PAN) or other nitrogen-containing polymers will be produced. The lethal dose of HCN is approximately 20 times lower than that of carbon monoxide (CO). The toxicity of HCN comes from the inhibition of cytochrome oxidase (an enzyme) activity and respiratory arrest from disturbed central nervous system functionality is usually the cause of its induced death [119].

The nature of fire products and yields depends on the amount of oxygen present in the combustion system. Above 12% oxygen, a significant amount of toxic CO will be released [121]. CO is undoubtedly an important toxic component of smoke and major threat in

fires. Although it is less toxic than some other gases, it is always very abundant. It combines with haemoglobin forming carboxyhaemoglobin. The affinity of CO for haemoglobin is about 240 times higher than that of oxygen. If even a small part of haemoglobin has been converted to carboxyhaemoglobin, this has a high impact on the oxygen carrying capacity of blood and the supply of this vital component [119].

Experiments done on polymers for the insulation of cables used in buildings (Hypalon, PVC, PE, PP, Teflon and others) indicate that these materials constitute in general a relatively low flammability risk in terms of flame spread rate or thermal exposure to their environment. However, most of them release smoke components that are both corrosive and toxic [134, 135].

'Rate of Heat Release' (RHR) determines the size of a fire and such data are key to computer fire models. In principle, a reasonably sized sample is exposed to such radiation (up to 100 kW/m^2) with an igniting flame and the heat generated by the burning sample is measured over time intervals [123, 136-138]. The burning of the materials used in construction yields a nearly constant value of 13.1 MJ energy per kg of oxygen consumed. A set of equations was developed for an 'open system' which is not dependent on controlling the oxygen input to the system, but only for measuring the oxygen 'deflection' of the output gases [139, 140]. Some RHR data on polymers are presented in **Table 7.4**.

The limited oxygen index (LOI) is defined as the minimum concentration of oxygen in an oxygen-nitrogen atmosphere, necessary to support a flame [141]. The test is carried out on

Table 7.4 RHR data of polymers [123]

Polymer or composite	Sample orientation	Test heat flux, kW/m^2	Total RHR, MJ/min.m^2		
			3 min	5 min	10 min
PVC cover on neoprene	Horizontal	10	1.8	3.0	4.8
		20	5.4	7.7	14.5
GRP composite	Vertical	20	1.9	12.8	16.4
Melamine laminate	Vertical	20	6.9	9.7	10.0
		35	15.9	18.5	22.2
Neoprene glazing gasket	Vertical	35	5.6	11.5	25.8
GRP: Glass fibre reinforced plastic					
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Table 7.5 LOI data for some polymers [142-144]	
Polymer	**LOI**
POM	15, 16
PMMA	16, 17
PP	17
PS	17, 18
PF	21
Polyvinyl alcohol, PVA	22
Polyamide 6	25, 26
EP (filled with 50% Al_2O_3)	25
PVC (rigid)	45, 47
Polyvinylidene chloride	60
PTFE	95

a film specimen in a variable mixture of oxygen and nitrogen. Work was done to determine which change in gas composition alters the burning characteristics of the polymeric material from a self-extinguishing to burning classification. LOI relates the relative flammability of a material to any other one provided that the material was able to burn in pure oxygen [142]. Polymer LOI value (**Table 7.5**) is not an absolute measure for the flammability and combustibility, it is affected by the sample thickness, pressure, flame temperature, heat capacity, thermal conductivity, melting temperature, and the existing additives beside its composition. For some polymers like PE, PMMA and PS, LOI values are independent of thickness in the range of 0.2 to 1 cm and decrease only slightly with smaller thicknesses. For epoxy, polyimide and PF, LOI decreases with the increase of the temperature [143].

Flammability tests for polymers are discussed in detail in other papers [119, 120, 123, 138, 143-152].

7.4.1 Flammability of Polymer Foams

The wide acceptance of polymer foams in construction has led to the necessity of developing such materials of low combustibility often combined with a low smoke evolution during fire. Their characterisation from the point of view of fire safety is a very complex task because of the fact that such materials can potentially be exposed to a large variety of ignition sources and circumstances and the environment influences their performance in a fire.

A relatively large amount of unfavourable publicity has appeared in the media related to their flammability, smoke and toxicity aspects. Examples are the major fire in 1992 at a vegetable processing facility in Yuma (Arizona, USA), in 1996 at the international observatory in Hawaii, in 2002 in nightclubs in Chicago, Rhode Island and Bali. Producers of polymer foams have made determined efforts to demonstrate that these products do not present an unacceptable fire hazard when properly installed and maintained [153, 154].

The fire behaviour of polymer foams is largely dependent on their exposure to air and is dominated by the characteristic low thermal inertia which permits the surface to respond very rapidly to any imposed heat flux and consequently ignition; maximum rates of burning can be achieved very quickly. Approaches toward reducing the flammability of polymer systems, in general, can be grouped in several categories [25, 142, 155-176]:

- Dilution of the polymer with non-flammable additives, such as mineral fillers.
- Incorporation of materials which decompose when heated, to release non-flammable gases such as nitrogen, or carbon dioxide.
- Addition of flame retardants which catalyse char rather than from flammable products.
- Tailoring polymer macro structure which favours char formation.
- Incorporation in the foam of additives able to stop the free radical chain reactions which occur during combustion.
- Formulation of products, which decompose thermally with a net endothermic reaction.

The most common route to improve the non-flammable behaviour of polymer-based products including foams is the addition of flame retardant. A number of basic types of flame retardant additives are in commercial use such as: phosphorus containing products, halogen containing additives, mixtures of halogen compounds with antimony oxide, nitrogen and boron compounds, alkali metal salts, hydrates of metal oxides. Some synergistic interactions between flame retardant can be expected to lead to efficient systems [25, 156, 157]. Studies were done also on ternary reactions among polymer, organo-halogens and metal oxides in the condensed phase under pyrolytic conditions [158].

Flame retardant additives operate in several ways. The minerals are resistant to fire and absorb heat. Due to the fact they are likely to be good heat conductors, they carry heat rapidly away from local hot spots, thus preventing or delaying the possibility of the temperature rising to the ignition point. For example, hydrated alumina whose decomposition retards the raising of temperature until the water evapourates. Aromatic

additives are able to sometimes form char in a cellular form that insulates the substrate against heat and access by oxygen, thus reducing the chance of fire. Flame retardant additives interfere with the mechanical integrity of plastic products and often require reinforcement to salvage strength.

The relatively low temperatures of manufacturing of PS foams (120 °C for expanded and about 200 °C for the extruded one with physical blowing agents) enable the less thermally stable aliphatic and cycloaliphatic bromine flame retardants such as hexabromocyclohexane or dibromoethyl dibromocyclohexane to be used. Using NH_4Br an important increase in LOI of PS was obtained [158]. Brominated flame retardant is highly effective in improving fire safety cost-effectively [177]. PS foam can produce molten drips (especially in ceiling applications) and with some formulations these drips burn. However, the presence of bromine containing flame retardant is able to delay the ignition of molten PS. However, in large fires PS foam burns with the generation of a dense smoke. If the foam is behind plaster or concrete facings, the extent of burning is usually limited to a small area near the original site of the fire [148].

Improved technologies of manufacturing PU foams led to the use of reactive flame retardants, which have the advantage over the additive flame retardants of providing a permanent effect. Polyols, isocyanates containing phosphorus, halogens (usually bromine) or both are the most used reactive flame retardant [33]. PU foams containing such flame retardant have to be produced with technologies, which exclude completely the presence of the water because of their sensitivity to hydrolysis. High levels of brominated aromatic ester polyol result in lower flame spread and smoke, but generally, with reduced physical properties and poorer dimensional stability (**Figure 7.4**). With phosphorus flame retardant in the presence of sodium molybdate the toxicity of pyrolysis and combustion products decreased [178].

Phosphorus containing flame retardants are used as phosphates, phosphonates, phosphines and phosphinic oxides. Halogen-containing phosphate esters such as bromine and chlorine in the form of tris (halogen alkyl) phosphates are popular [33]. The effects of phosphorus and brominated additives on flexible PU foam were compared [179]. Melamine has broad utility as a flame retardant additive in flexible PU foams [180].

The fineness of the fire retardant particles and the state of development of the polymer product surface have a significant influence on their ignition and combustibility. However these aspects have not yet been investigated to a satisfactory extent [181, 182].

PU foams do not melt in a fire but burn to produce pyrolysis gases, dense smoke and some char. The rate of their burning depends on the type and amount of fire retardant present in the foam.

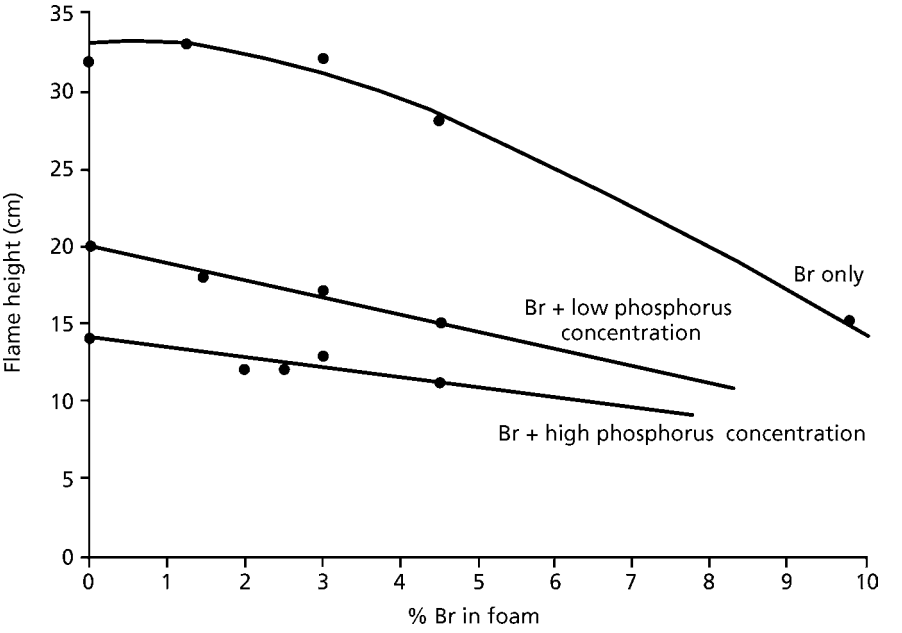

Figure 7.4 Effect of fire retardants on flammability of PU foams [153] (*Reproduced with permission from P.J. Briggs, Cellular Polymers, published by Rapra Technology Ltd., 1985, 4, 265*)

PIR foam behaves similarly to fire retarded PU foam in the early stages of a fire, but the char formation significantly restricts the spread of the fire. Recognition of the efficient fire barrier characteristics of glass fibre reinforced PIR foam chars has allowed new PIR formulations even some without flame retardants. Such composites generate less smoke than PIR foam.

The presence of ammonium polyphosphate and melamine cyanurate filler causes a slight worsening of the physical and mechanical properties of PU and PIR foams but the fire behaviour of flame retarded foams is better than that of unfilled foams. In particular the use of the previously mentioned mixture, which produces a synergistic effect causes a significant improvement of the fire performance. This is characterised by a remarkable decrease of RHR and weight loss without worsening smoke opacity and toxicity [183].

PF foams offer to the construction industry a useful combination of physical and flammability characteristics. They generate low levels of smoke in most fire tests. It was reported that a cupric complex of a macro heterocyclic compound is an effective stabiliser for thermo-oxidative decomposition of PF foams above 200 °C. An amount of 0.25-5.0 pph permits significant decrease of ignitability [178].

Table 7.6 Flammability data of rigid foams with 35 kg/m³ density [153]				
Flammability test	**EPS**	**PU**	**PIR**	**PF**
LOI	28	24	30	46
Flash ignition temperature, °C	345	285	415	490
Self ignition temperature, °C	490	500	510	450
Flame spread (horizontal burning), mm	37	125	10	14
Smoke maximum obscuration, %	80	85	30	3
Smoke density in non-flaming mode	25	120	70	8
Smoke density in flaming mode	300	330	130	10
Reproduced with permission from P.J. Briggs, Cellular Polymers, published by Rapra Technology Ltd., 1985.				

Some flammability data [153] of expanded PS (EPS), PU, PIR and PF foams are presented in **Table 7.6**.

Chemical modification of UF foam and the use of inorganic phosphorus and nitrogen containing flame retardants are a general approach to UF flame retardancy. Hardly combustible UF foams with closed cells were developed by chemical modification and by adding 1-2 pph of phosphorus compounds. Using a level of 2-2.5 pph, an important increase of time for the beginning and termination of burning process was observed [178].

The fire performance of plastics as electrical insulating materials was recently studied [184]. Short circuits or ground faults were responsible for the largest percentage of thermal and acoustical insulation (normally in a concealed space), fires in buildings. The largest share of the civilian injuries occurred in fires began by cutting or welding too close to combustibles [185].

Although still a relatively new area of development, the polymer nanocomposites show great promise as fire retardant materials. Not only can the combustion properties of the materials be modified but in many cases the mechanical properties are also improved [186, 187]. In such product with about 3% clay, the RHR decreases 20-60%, depending on polymer matrix without affecting at this loading the mechanical properties [188].

7.4.2 Flammability of Composites

The polymer matrix is by far the most important component of the composite in determining the combustion characteristics. Under fires, the glass fibre doesn't burn and

does not, therefore contribute to the combustion of the glass fibre reinforced polymer (GFP). The other common fibre reinforcements, carbon, aramid, ultra high molecular weight PE (UHMWPE) will burn under normal fire conditions, but their contributions to the fire are generally much smaller than that of the matrix [189].

Fibre reinforced polymers (FRP) were found to generate higher amounts of products associated with incomplete combustion such as carbon monoxide and smoke, compared to ordinary combustibles [190].

The fire characteristics of many FRP with different matrices and various fibres have been studied [191-195]. Heat resistant composites with very low smoke density, toxicity and corrosivity were obtained with a group of flame retardants (based on dihydrobenzoxazines) which don't contain halogen, sulfur or phosphorus [196]. Also, glass fibre reinforced resole phenolic composites have some outstanding fire properties, e.g., low RHR and low toxic smoke emissions [197].

Intumescent technology emerged in polymer science comparatively recently as a technique ensuring the fire protection of polymers and composites. Intumescent systems stop the combustion at an early stage, i.e., at the stage of thermal decomposition which is accompanied with the release of flammable gaseous products. The intumescent process consists of combining carbon (coke) formation and swelling of the surface of the burning polymer [198]. A coating of intumescent resin retards the combustion of the organic components present in GRP composites and also significantly reduces the area affected by the flame, drastically reducing the volume of smoke and practically eliminating burning. The specially formulated resin gives fire protection by foaming in situations where GRP laminates are exposed to direct flaming. The resin can be applied by brush as a flow coating, normally to the reverse side of the building panel where it will provide fire retardant properties. Mineral fillers impart varying degrees of flame retardancy to GRP [199]. An inorganic intumescent coating was developed for the protection of FRP. This one releases only water vapour when it is exposed to fire, so it is safer than organic coatings [200].

7.5 Environmental Hazards

There is a two-way relationship between plastic materials and the environment. The first one, which is well studied, is known as weathering: that means the effect of the environmental factors on plastics that leads to their ageing during outdoor exposure. The second one deals with the effects of plastics and their additives on the environment [69, 74, 201, 202].

The effect of plastics on the environment is manifested outdoor and indoor. The most important outdoor effects come from: plastics industry emissions, the ozone depletion

produced by halogenated additives in plastics and other products, potential production of dioxins and furans on the incineration of PVC in mixed municipal solid waste streams, and from disposed of end-of-life plastic products in sanitary landfills [203].

The indoor environment polluted by emissions from organic polymeric building materials such as plastics, paints, adhesives, wall covering, etc., have a strong impact on the indoor air quality (IAQ) and from it on people's comfort and health. IAQ is an important determinant of population health and well being but in spite of this, its control is often inadequate. Presently, few of the hundred known IAQ pollutants have been addressed directly by guidelines. From the draft of World Health Organisation (WHO) statements it follows that national and international organisations have an obligation to establish criteria for acceptable IAQ [204]. Allergies, other hyperactive reactions, sick building syndrome (SBS), airway infections, lung cancer, etc., are associated with IAQ in buildings [205]. The term SBS has come into vogue during the past several years and refers to complaints of illness made by building occupants [206].

More information on this subject is presented in Chapter 10, and additional references are also provided on this topic [207-236].

7.6 Recycling

For ecological and economical reasons, materials recycling is of great importance as an integral component of plastics waste management.

The economic driving forces for recycled plastics have been anything but constant during the last 50 years due to large fluctuations in prices of virgin materials and supply. Early recycling efforts were seen only as a means of lowering material's consumption within the industry by mixing clean, uncontaminated processing waste with virgin material. During the 1960s, virgin material prices fell abruptly and recycling activities stagnated. In the 1970s they picked up again as an oil embargo caused material shortages. During the late 1980s material prices decreased again. As legislative pressure on industry and consumer preferences are evolving, however, recycling is becoming less of an option and more of a necessity and business opportunity [201].

Plastics became in the 1990s the symbol of a throwaway society and were regarded as a major culprit of the landfill crisis. The response of the industry is plastics recycling [237-241]. Severe restrictions are being imposed on two of the most popular waste management techniques, landfill and incineration [201].

Plastic building products occupy the second place in quantity of residual plastics in municipal waste [242]. The important benefits of polymer recycling consist in a reduction

of waste generation, less need for landfills and from an economic point of view a reduction of the consumption of resources. However the amount of used plastic waste from the construction sector is likely to increase in the future and so issues relating to recycling need to be addressed [243].

The life cycle of most plastics starts with the extraction of natural gas or crude oil. The latter one is cracked into naphtha which is refined into ethylene, propylene, styrene, benzene, etc., the basic polymer feedstock. The next step is polymer synthesis followed by the third one, polymer processing into different items for application and consumption. Sooner or later, all plastics end up as waste that can be incinerated, dumped (land filling) or recycled and re-used [241, 244]. The recycling of plastics and all polymers in general is important to both conservation of materials and conservation of energy [245]. In Europe the amount of plastics in the municipal solid waste is about 10% (in weight), PE and PP representing 55% of the total and PVC, 25%. As we can see from the **Table 7.7**, the building plastic wastes are in second place after the packaging waste [242].

Table 7.7 Origin of residual plastics in municipal waste in % [242]

Packaging	25
Building	21
Electricity - electronics	15
Gum, varnish, painting	10
Automobile	7
Furnishing	5
Agriculture	4
Miscellaneous	13

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Recycling of plastics can be done chemically or mechanically [245-248]. Chemical recycling is based on techniques which degrade the macromolecules (pyrolysis, oxidation, combustion for energy recovery, etc.), leading to monomers (like styrene, methyl methacrylate) which are able to be reused in polymerisation technologies or to produce oil-like products. In the case of mechanical recycling, products are melted down, while the polymer itself doesn't suffer any change. Only thermoplastics which form the highest

volume of the waste, qualify for this type of recycling. A type of recycling of plastics by surface refurbishing (coating application, polishing) [249] was also proposed. It is recognised that a variety of recycling and recovery processes will be required in order to be able to deal with scrap composite material from a wide range of sources and in varying quantities [250]. So far processing of mixed plastics wastes, such as 'tailings' from municipal solid waste (MSW), after minimum refining has seen uses in building as timber replacement ('plastic lumber') [251].

Recently a fluorescent tracer system was proposed for automatic identification and sorting of waste plastics [252]. The system is based on the following three elements: the use of selected tracers in the polymer, a high speed system for identification of the tracers, a process for automatically separating the plastics identified.

The reluctance of most polymers to mix with one another has important ramifications in the plastics recycling technologies. Sometimes compatibilisers are necessary. While some believe it is simply an industrial conspiracy that prevents recycling of plastics, it is actually quite difficult to achieve [253].

7.6.1 Recycling of Some Polymers Used in Building

A technology (Encap) has been developed that will remove expanded PS and other expanded polymers from the waste products. This process represents a cost-effective means of solving a major environmental problem associated with producing and recycling foams and other plastics. It mixes ground, recycled expanded PS and other recycled cellular plastics with a proprietary phenolic resin hybrid, and pours them into a mould, and after remoulding the resulting item can be used [254]. The applications suggested for this technology are: roofing, insulation sheathing for wall and low-slope roof assemblies, stress skin panels to wood, or cardboard for structural purposes, sound absorbing and decorative for furniture wall systems.

Research done by the PU industries has shown that there is a range of technology options for manageing PU wastes in addition to the practice of land filling. Chemical recycling (glycolysis, hydrolysis, etc.), mechanical recycling and energy recovery are the main options under development [255]. Economically and environmentally sustainable closed-loop chemical recycling of PU has been a goal of the PU industry for many years [256].

For low density, flexible high resilient and rigid PU foam post-consumer wastes, a modified solid state shear extrusion (SSSE) technique was applied for their pulverisation. The fine powder obtained can be used as a filler and/or reinforcing material for polymers and mineral products with improved mechanical properties [257].

PVC has been produced for more than 50 years on an industrial scale, and it lies in second position behind PE and thus numbers among the most important commodities. Its applications in building include pipes and fittings, profiles, window and door frames, flooring and roofing products. The building and construction industry in Western Europe represents around 52% of PVC use. Approximately 70% of PVC applications have an expected service life of more than 10 years, foremost among them being products for the building industry. Only about 15% of applications, especially those from the packaging field, have a short service life of less than two years.

As for the major PVC flows, several recycling schemes mainly based on mechanical recycling have been and will be set up, particularly in the northern EU countries (notably Scandinavia, Germany, Austria and the Netherlands). These schemes rely on covenants between the authorities and the PVC industry, or voluntary incentives of the PVC industry. The potential of PVC waste (pure resin) for chemical recycling in ktons in the period 2000-2010 is given in **Table 7.8** [258].

Table 7.8 The potential PVC waste (pure resin) for chemical recycling in ktons in 2000-2010 [258]

Waste type	**2000**	**2005**	**2010**
Pipes	39	60	87
Window profiles	31	52	84
Other profiles	191	260	333
Cables	11	15	20
Flooring	186	211	243
Roofing	8	9	10
Total	**466**	**607**	**777**

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At the end of the service life, what remains is a PVC waste, which is contaminated, often inextricably, with other materials. Not only is a second life possible, but also a further ten or twenty years depending on the degree of the new treatment to meet the specified quality of a new product. Generally the processor wants to use recycled PVC having a quality matching that of the virgin polymer. Since this is hardly feasible in practice, two possibilities remain for using the recyclate, the choice depending on its quality: reprocessing as 100% recyclate or blending with virgin PVC. Nevertheless several applicable criteria can be stipulated which

determine both the direction and limits of recycling: sorting by MW or by colour, size reduction and pulverisation, compatibilisation or by contamination with other materials [259].

For collecting purposes with a view to recycling of PVC waste, it is recommended that a single material is used, for example window profiles [260-263]. Complete PVC window frames are made of 38% PVC, 34% glass, 24% metal, 4% other materials. Such a frame contains 18 kg PVC [264].

The mechanical properties of recycled PVC are detrimentally affected by the presence of contaminants which act as stress concentrators and so cause premature failure upon loading. Pulverisation of the recyclate to reduce the size of such impurities results in improved properties that compare with those of pure grades. Often contaminants can be other polymers such as PET, PE, paper, and so on [265]. In many countries especially European countries, PVC windows are now the first choice, ahead of those made from conventional materials and recycling is increasing to meet this demand. Thanks to their life span of up to 40 years without necessary maintenance, the qualities of these window frames currently entering the waste stream are modest. This will increase over time as more are used and as the windows, which were installed in the sixties, enter the waste stream. Germany already has automated plants for recycling PVC window frames.

The recycled polymer can be used in new frames making up the core layer (two-thirds by weight) while virgin PVC forms an external layer in a coextrusion process. These profiles perform just as well as those from the virgin polymer and, after another 10 years of service, are ready for another recycling loop [259, 263].

PVC pipe producers have been collecting PVC pipes that have been used for 10, 20 or 30 years but far from having reached the expected service life which is 100 years and more. Large quantities of used PVC pipe are expected at the earliest beyond 2010. The processing of recycled PVC pipes through coextrusion is convenient for layered products with virgin PVC on the side contacting with other materials, and the recycled one on the other side [266].

Manually sorted PVC scrap flooring can be coarsely and then finely ground. Sieves and wind sifters are used to remove plaster, glass cloth, adhesive residues and other adhering contaminants, so that this treatment step yields a PVC flooring recyclate whose purity is higher than 99% including fillers. The recyclate is reformulated with added plasticisers, fillers and serves as a dry blend for new, calendered PVC flooring. Such multi-layer PVC flooring may contain up to 70% of recyclate material.

Experience gained over the next few years will show how far recycled material from scrap roofing membrane can be re-used in new roofing membranes, tunnel membranes, protective membrane, civil engineering membrane, and so on [257].

Another segment for recyclate is the substitution of conventional construction materials such as hardwood, non-structural lumber, or concrete. It is precisely the plastics specific characteristics from which technological advantages can be derived, leading to a low system cost as long as a comparable lifetime can be achieved [251, 267, 268].

There have also been attempts to chemically recycling PVC scrap [269].

7.6.2 Reclaim Plastic Scrap

The fear of the waste crisis in the late 1980s helped to create the thermoplastic scrap reclaiming business. Most processing plants have to reclaim reprocessable scrap, flash, rejected parts, etc. The goal is to eliminate scrap, because it has already cost money and time to go through the process. The reprocessing starts with the transformation of scrap in pellets, by using a granulator. Blending the reclaimed material with the virgin one definitely influences and can significantly change the melt processing conditions and the performance of the end product [270, 271].

7.6.3 Biodegradable Plastics

Environmental awareness has led to the design and development of degradable plastics [271]. Biodegradable polymers are completely degraded via microbial attack. The term 'biodegradable' has in recent years become part of the 'green' vocabulary.

New concepts are now known in material sciences and materials degradation such as [272]:

- The production of materials which must have strength and functionality while in use but which become degradable after service.
- Polymers should come from renewable resources instead from petroleum.
- Save materials by improved product design and by recycling.

To achieve degradability, the units (mers) of the macromolecular chains have to be sensitive to hydrolysis and oxidation at higher temperatures. Some polymers are sensitive to biodegradation by enzymes and/or microorganisms while others in later stages of deterioration can be biodegraded. Addition of biopolymers to synthetic polymers can provide susceptibility to auto-oxidation due to the porous matrix left after the degradation of the biopolymer. Combining several methods of degradation in a material is a successful mode of rendering a plastic degradable [273, 274].

A degradable plastic undergoes disassembly that becomes part of the ecosystem carbon cycle in appropriate waste management infrastructures. For example, a biodegradable plastic would degrade into carbon dioxide and biomass (compost) in a composting infrastructure [275, 276].

Among biopolymers, in many cases polysaccharides are used, increasing attention is being given to more complex carbohydrate polymers produced by bacteria and fungi, especially to polysaccharides such as xanthan, curdlan, pullan and hyaluronic acid [277, 278].

7.7 Repair and Maintenance

Building materials, mainly the conventional ones like concrete, timber, or metals need service repair and maintenance during their life. Concrete, in spite of being the most extensively used construction material, has not proved to be as durable and maintenance free as one would have liked. An increasing number of buildings develop signs of distress within a few years after their construction, mainly when built in locations subject to an aggressive environment. Factors such as design inadequacies, poor workmanship, use of low quality materials, and poor maintenance practices, besides corrosion of reinforcement are the major causes for the rapid deterioration of many structures [279]. Once cracking or other manifestations of deterioration are visible, the concrete is more susceptible to further damage, which may eventually render it unsuitable for further use. Although it is obvious that economic and political considerations will be important in decisions on maintenance and repair, from a technical point of view early maintenance is desirable for maintaining its integrity. Preventive maintenance consisting of regular inspection and restoration of sealed joints, drainage systems, etc., will play an important role in the durability of concrete [280].

The important matter in repair is to establish the nature and severity of the service environment, to properly assess how much degradation has occurred, and to reasonably estimate the intended service life. From these and known relationships of environmental influences on building materials, techniques can be developed to give a repair that will have a reasonable probability of success.

Economic considerations have made it mandatory to look to repair the damaged concrete rather than it's total replacement.

The repair of concrete can be done by:

- Injection grouting of cracks.
- Patching up of damaged surfaces.
- Coating of concrete surfaces and reinforcing bars.
- Replacing of deteriorated concrete and reinforcing bars.
- Using new polymer-concrete composites.

7.7.1 Injection Grouting

This technique involves the following stages:

- Assessment of the cause of cracking and structural significance of the crack.
- Injection of the resin (EP, PU, etc).
- Assessment of effectiveness of the repair by ultrasound testing and examination of cores obtained from the repaired structure.

So far EP resin injection has proved to be an effective technique for repairing cracks in structural members such as walls, piers, floors ceilings, and so on [281].

A comparison was recently made between resin injection that is done manually and self-repair in which the adhesive for repair is already present in the matrix at the time the cracking occurs. Self-repair adhesives with higher modulus of elasticity transferred stresses well across the crack width allowing the crack to sustain as much, if not more, as the original loading (as measured by specimen strength). The adhesives with lower modulus of elasticity (more flexible) also transfer the stresses [282].

7.7.2 Patching

Patching refers to the restoration of relatively small areas of damage to the profile of the surrounding concrete. Surface preparation of the substrate is critical. Portland cement mortars and grouts, including various preparatory products which contain a variety of cementing and filler ingredients are the most frequently used materials. Latex modified mortar and epoxy mortar is often substituted for cementitious patching materials when a fast cure time, higher bond strengths and some feather edging is required. Some times acrylic, styrene-butadiene copolymer, polyvinylacetate (PVAc) lattices are preferred [283]. It was also reported that repair mortars using redispersible polymer powders for concrete structures show high resistance to the diffusion of chloride ions, oxygen and carbon dioxide, and also low shrinkage [284].

7.7.3 Coating

It is now widely accepted that the inherent chemical resistance of concrete is limited and that the concrete surface needs additional barrier protection when exposed to aggressive environments. Unlike the metallic substrate, the concrete substrate is heterogeneous and porous in nature. Protective barrier systems protect concrete from degradation by

chemicals and subsequent loss of structural integrity, prevent the staining of concrete, and protect liquids from being contaminated by concrete [285]. Painting a concrete surface can increase its resistance against pollutants and acid attack.

Many types of coating are available which exhibit varying degrees of chemical resistance, durability and ease of application. Intumescent coatings are also used in the repair of fire damaged structures. Some of the more widely used products are bituminous coatings and mastics, polyesters and vinyl esters, PU, EP, polychloroprene, coal tar, acrylics, and so on [281].

Reinforcing steel bars need protection against corrosion. Powdered polymers like EP are applied by fluidised technique. In this process air is used to force powdered polymer into the heated surface of the object, which is in the upper section of a closed tank. The coated object is removed and heated in an oven to assure a continuous coating.

7.7.4 Repair with Polymer Concrete

Due to the possibility of tailoring its properties to suit any particular situation, and also owing to its excellent chemical stability and high bond strength, polymer concrete is a successful repair material.

It is recommended that all unsound concrete be removed and all surfaces to which polymer-concrete will bond to be cleaned preferably by sand/shot blasting and dried.

The polymer-concrete repair can be carried out in the following ways:

- Dry pack system containing aggregates and a low viscosity monomer or oligomer.
- Premixed polymer concrete in which the aggregate and monomer (or oligomer) are mixed together in a wheelbarrow or a conventional concrete mixer and then directly applied to the concrete surface. This system results in a more cohesive and uniform mix and is more popularly used in practice [279].

Latex modified mortar and EP mortar is often substituted for cementitious patching materials when a fast cure time, higher bond strengths, and some feather edging is required. Then properties can be adjusted within fairly wide margins by suitable formulation so that they can be tailored to fit the job at hand.

A relatively new repair technique for concrete structures, including prestressed structures, consists of externally bonding flexible sheets of FRP composites to the concrete surface. Depending on the type of application, the function of the externally bonded reinforcement

can be any combination of strengthening, stiffening, crack arrest, or corrosion protection. This technique originated from the strengthening of steel beams with EP adhered steel plates [286, 287].

7.7.5 Metals Maintenance

Maintenance of metals is done to avoid corrosion which is defined as destructive and unintentional attack. The problem of metallic corrosion is one of significant proportions; in economic terms, it has been estimated that approximately 5% of an industrialised nation's income is spent on corrosion prevention and the maintenance or replacement of products lost or contaminated as a result of corrosion reactions.

Prevention and maintenance in this case is done by anodic or cathodic protection or by the application of organic coatings made of polymers. The protective value of a coating depends on its chemical inertness to the corrosive environment, good surface adhesion, impermeability to water, salt and gases, and the proper application technique. Providing the coating is continuous and uniform, its impermeability depends directly on its thickness. At low thickness, it is difficult to avoid the presence of pinholes and discontinuities in the coating, particularly over the sharp edges, projections, welds, crevices and other irregularities normally present on surfaces.

7.7.6 Repair of Plastics and Their Composites

It is often necessary to join two or more plastic components or to repair a broken part. For some thermoplastics solvent welding is applicable. The process uses solvents which dissolve the plastic to provide molecular interlocking and then evaporate. Normally it requires close-fitting joints [25].

The techniques for repair and joining plastics and composites can be divided into mechanical joining (based on the use of metallic or polymeric screws), adhesive bonding and welding. Various welding processes such as hot plate welding, hot gas welding, extrusion welding, implant induction (electromagnetic) welding, resistive implant welding, ultrasonic welding, linear and orbital vibration welding, spin welding, radio frequency welding, infrared and laser welding, microwave welding, are available [25, 288].

7.8 Smart Materials and Structures

Due to some properties which are close to those of biological materials, and their response to the environment, some chemicals, polymers and composites have more recently been

considered as smart materials. The smart materials field is a new area of materials science and engineering and hence the number of concepts is not finally established. Its development is advancing based on conceptual and fundamental research in materials and technology of manufacturing [289].

The expression smart materials and structures is widely used to describe the unique marriage of materials science and structural engineering by using sensors (mostly based on optical fibres) and actuation control technology [287].

It is considered that the smart materials will have an important series of functions such as sensory, processor, executive functions, information transfer, energy transformation, etc. A great deal of smart materials work is still in the research stage. So far conductive (conjugated) polymers appear to be the largest area of growth but their manufacturing continues to be expensive [290]. Also the blending of non-covalent interactions with traditional polymer chemistry can lead to a novel class of smart (responsive) materials allowing a new access to high technology applications [291].

The field of smart materials and structures is emerging rapidly with technological innovations appearing in engineering materials, like sensors, actuators and image processing. Smart materials can be defined in several ways [292]:

- Materials functioning as both sensing and actuating.
- Materials which have multiple responses to one stimulus in a coordinated fashion.
- Passively smart materials with self-repairing or stand-by characteristics to withstand sudden changes.
- Actively smart materials utilising feedback.
- Smart materials and systems reproducing biological functions in load bearing systems.

It appears that smart structures offer a potential solution for continuous structural health monitoring. A smart structure is defined as a system that is designed for a specific functional purpose, and that operates at a higher level of performance than its conventional counterpart in fulfilling this purpose. The system senses its internal state and external, and based on information obtained makes decisions and responds to meet the functional requirements [293].

Until recently, researchers from different disciplines have made intensive efforts to develop smart structures able to measure their own structural condition by using embedded optical fibre. Such composite systems are able to assess damage and warn of impending weakness in the structural integrity of the structure. Constructions built with such materials with self-

optical nerves can monitor their own mechanical and thermal properties. In civil and building engineering the embedded optical fibres can improve concrete evaluation and enable immediate condition awareness for service assessment of the structural integrity [287].

Recent studies indicated that carbon fibre reinforced concrete-based material could function as a smart material for real time diagnosis of damage. The electrical signal is related to an increase in the material's volume resistivity during crack generation or propagation and a decrease in the resistivity during crack closure. The change of electrical characteristics reflects large numbers of information of inner damage of concrete-based material, which can be used to detect potential damage and prevent fatal failure [294].

It was established that the performance of smart structures depends on the quality of the bonding along the interface between the main structure and the attached sensing and actuating elements [295].

7.8.1 Examples of Smart Materials

The vibration damping properties of composite beams were investigated using interfacial adhesive showing the optimum bonding condition between the beam and the piezoelectric zirconate titanate (PZT) sensor and actuator having different material properties. An optimum bonding condition is one of the most important factors in manufacturing smart structures. Good adhesives used in structural composites are able to contribute to the transfer of the structure elastic deformation. Among others, epoxy adhesive showed the fastest response speed and most stable frequency curve, meaning that it can provide the optimum interfacial bonding [294].

Functionalised conjugated polymers such as polythiophenes were studied from the point of view of the detection and transduction of chemical and physical information into an optical or electrical signal. Their ionochromism (reversible change of colour in the presence of ions), photochromism (reversible change of colour on exposure to light), affinity chromism (tendency to colour change) and electroluminescence of polythiophene complexes with crown ethers and other solutions are discussed in detail [295].

The basic polymer principles related to smart polymer flame retardancy and the relationship between flammability and polymer structure are also reviewed [296].

Conductive polymers have been produced to develop smart windows by electrodeposition of various high conductivity polymers on transparent conductive substrate. A suspended particle device that enables users to control the passage of light through glass or plastic windows has been commercialised. The specially treated panes can also be used to shield instrumentation. In such systems a polymer film between two panes of glass or plastic is

connected to an electrical current. By turning the voltage up or down, one can increase or decrease the amount of light being transmitted through the window. When in an on state, the particles will align and the view through the glass or plastic will change from opaque to clear. If only a partial voltage is applied, then the viewing area becomes only partially clear [290].

An overview on supramolecular polymer chemistry is presented in combination with a discussion of several potential smart systems based on hydrogen bonding and metal-ligand interactions. For a particular system, terpyridine-metal, the switchable properties are discussed in [291].

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8 Sustainable Construction

Charles J. Kibert

8.1 Introduction

The rapidly growing sustainable construction movement is affecting the design and construction of buildings in many countries worldwide. Sustainable construction is simply the design and operation of a healthy built environment using ecologically based principles. It is alternatively referred to as green building, ecological design, and ecologically sustainable design. It has two key components: environmental protection and resource-efficiency. Contemporary sustainable construction considers five categories of resources: land, materials, landscape (biota), energy, and water. These are the 'stuff' of the built environment and the essential components that are used to create and operate it. Using these resources 'efficiently' means that the need to extract material resources from the biosphere is minimised, that energy as much as possible is derived from renewable sources, that land is used to preserve biodiversity, biological function, and natural system services. Resource-efficient design is the process by which planners, architects, engineers, and others describe the location and content of buildings to use resources efficiently.

8.2 Resource-Efficiency and Sustainable Construction

Sustainable construction is defined as '...the creation and operation of a healthy built environment based on resource-efficiency and ecological principles'. In fact resource-efficiency and ecological principles are coupled and must be considered together. Sustainable construction is in effect the efforts by which the construction industry supports sustainable development. Clearly, and as is spelled out in its definition, sustainable construction is of primary importance for achieving sustainability in this industrial sector. In most industrial countries, buildings consume in the order of 40% of the nation's primary energy for their operation. In the US, buildings consume 30% of primary energy supplies because transportation takes a larger portion of energy than in other nations. In terms of materials, the built environment absorbs about 40% of all extracted materials in industrial countries and probably higher percentages in developing countries. It has been estimated that the built environment contains as much as 90% of all materials ever extracted in the US. The built environment can be a

major source of resources for future generations or a major disposal headache. In addition to materials and energy, the built environment is a major consumer of land resources and its creation generally results in the destruction of significant biological resources. Consequently buildings have profound impacts on efforts to use resources more wisely.

8.2.1 Brief History of Sustainable Construction

The first description of sustainable construction emerged from the activities Task Group 8 (Building Assessment) and Task Group 16 (Sustainable Construction), both activities of Conseil International du Batiment (CIB), an international research networking organisation. These Task Groups, both organised in 1993, created international forums to enable collaboration among construction researchers and professionals to sort out the issues and priorities of an emerging class of high performance buildings that were beginning to emerge in the late 1980s and 1990s. The American Institute of Architects (AIA) established its Committee on the Environment (COTE) in 1989. In the UK, the Building Research Establishment (BRE) developed the first truly successful building assessment system in 1992. Known as Building Research Establishment Environmental Assessment Method (BREEAM), this system focused on commercial properties and represented the first attempt to differentiate the performance of green buildings from their conventional counterparts. In 1993 the US Green Building Council (USGBC) was started with the first conference on green buildings in the US being organised in March 1994. Additionally the USGBC initiated the process of developing a building assessment method for the US. Known as Leadership in Energy and Environmental Design (LEED), the final operational version was made available for use in early 2000 and has since been adopted by a wide variety of public and private organisations for guiding the design of their facilities. Task Group 8 held the *Buildings and Environment Conference* in May 1994 in the UK and Task Group 16 organised the *First International Conference on Sustainable Construction* in Florida in November 1994. These initial meetings were followed by numerous conferences on a wide variety of green building issues. Task Group 8 became Working Commission 100 (Building Assessment) and has since held Green Building Challenge conferences in Vancouver (1998), Maastricht (2000), and Oslo (2002).

8.2.2 Resource-Efficiency as a Key Concept of Sustainable Construction

The efficient and effective use of resources is an essential element of sustainability for the built environment. Buildings are storehouses of materials and have embedded in them a potential for consuming energy, water, and materials over their unusually long

lifetimes. When considering building products and systems, the entire life-cycle of the materials utilised in the building, from extraction to disposal, needs to be considered. Buildings differ from other human artifacts because they incorporate a significant number of high mass, low performance materials, the latter in the sense that comparatively massive materials are used to accomplish the intended function. For example, the built environment makes extensive use of fill dirt, aggregates, cement, concrete blocks, clay blocks, bricks and other similar low technology materials. The recycling potential for these types of materials is relatively low compared to metals and plastics. Consequently resource-efficiency, in the sense of being able to close material loops, is difficult to achieve due to the use of significant quantities of these high mass, cheap, and difficult to reuse or recycle materials.

Figure 8.1 illustrates how resource efficiency is the key issue for sustainability in the built environment and how resources can be evaluated using the seven principles shown on the 'Principles' axis [3]. The fundamental idea is to ensure the resources of construction are used in a sustainable manner throughout the life-cycle of the constructed artifact, from planning through to ultimate disposal in a sustainable manner. The physical resources needed to create constructed artifacts are: land, energy, water, materials, and landscaping or biota.

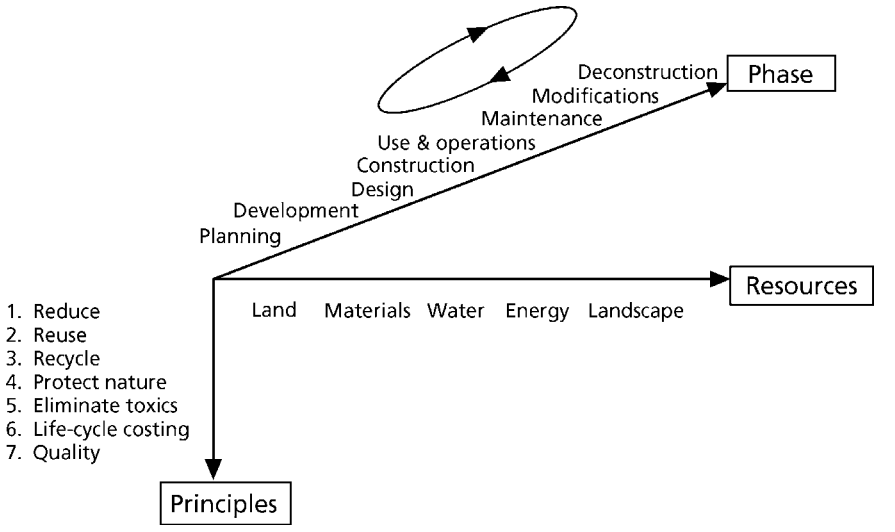

Figure 8.1 Framework for sustainable construction. Resource efficiency is the key and it is the application of the basic principles during all phases of the life-cycle of the built environment that provides the potential for sustainability.

Over the life-cycle of a building, significant resources will be consumed as it is used, operated and maintained. For example, in a typical building, the operational energy will amount to 5 to 10 times the embodied energy of the building's components. Virtually all the water consumed by a building will be by its occupants or by its landscaping over its lifetime. Landscaping is a greatly overlooked resource of the built environment and can have both positive and negative impacts. At one extreme the misuse of landscaping can result in significant water consumption and energy use for maintenance as well as biological consequences depending on the species selected for incorporation with the building. At the other extreme, landscaping can be integrated in with the building to provide a wide range of services that would otherwise have to be provided by human-fabricated systems. Among these services are passive heating and cooling, waste assimilation and processing, food production, and stormwater handling.

For the purposes of sustainability the end-stage of a constructed artifact is referred to as 'deconstruction'. Deconstruction is the disassembly of the building to promote the reuse and recycling of its material content, that is, to enhance the 'recycling potential' of its constituent materials.

The issue of resource conscious design is central to sustainable construction and the question to be resolved when designing under this paradigm is how to minimise virgin resource consumption and the resulting impact on ecological systems. The following is a brief summary of how resources can be considered for efficiency in building.

- ***Materials***: In terms of materials selection – closing loops and eliminating emissions (including solid waste) are the key concepts. The types of materials that account for the bulk of construction do not lend themselves to true recycling but to downcycling, that is lower value reuse. Aggregates, concrete, fill dirt, block, brick, mortar, tiles, terrazzo, and similar low technology materials are fortunately largely inert. More effort needs to be made to keep these low-end materials in productive use. Other than these high mass materials, most other building components are manufactured in factories and it is the design of these products plus their manufacture that must be examined for their resource impacts. For closed loop behaviour, products should be able to be easily disassembled and the constituent materials should be capable of and worthy of recycling. Because recycling is not thermodynamically 100% efficient, the recycled materials must be inherently safe for biological systems because dissipation into the biosphere of the residue is inevitable.

- ***Land***: Conversion of natural and agricultural land or 'greenfields' to built environment should be minimised and land must be 'recycled' in the sense that disturbed land such as former industrial zones (brownfields) and used or blighted urban areas (greyfields) need to be restored to productive use. Land use is also connected to patterns of development that either create efficient urban forms at one extreme or urban sprawl at the other. Urban sprawl leads to overdependence on the automobile

for transportation and significant fossil fuel consumption and emissions. Land also provides environmental amenities, biodiversity, and food. Over production of the built environment, coupled with inefficient layout of the built environment in the form of planning leads to excessive consumption of this very finite, important resource.

- ***Energy***: Energy in most cases remains the paramount issue for building design and has three general approaches that can be integrated:

  (1) Envelope resistance to conductive, convective, and radiative heat transfer.

  (2) Employment of renewable energy resources.

  (3) Passive Design. Passive design is perhaps the most critical of all of the aspects of resource conscious design because it uses building geometry, orientation, and massing (the arrangement of the building's mass on the site to be able to store solar energy) to obtain conditioning from natural effects such as solar insolation incoming solar radiation), thermal chimney effects, prevailing winds, local topography, microclimate and landscaping.

- ***Water***: In many areas of the world, the availability of potable water is the limiting factor for both development and construction. Only a small portion of the earth's hydrological cycle is comprised of a potable component and protection of existing ground and surface water supplies is becoming increasingly critical. Once contaminated, it is extremely difficult if not impossible to reverse the damage. Emphasis must be placed on low flow fixtures, water recycling, rainwater harvesting, and low water use landscaping.

- ***Landscape***: Landscaping can play an important role in resource conscious design because it can supplant conventional manufactured systems and complex technologies in controlling external building loads, processing waste, absorbing stormwater, providing food, and of course, providing environmental amenities.

8.2.3 Resource-Efficiency Economics

One of the key challenges of sustainable construction is demonstrating the economic advantage of choosing resource-efficient strategies over conventional approaches. It is clear that high performance buildings that are well-designed in an eco-efficiency sense will most often have lower total lifetime costs than the typical alternatives. Although the initial costs will sometimes be higher, the operational costs are usually significantly lower. Additionally creating a healthy built environment, a key concept of sustainable building, provides significant additional benefits such as increased productivity and lower absenteeism. A typical US office building will lease for $\$220/m^2$ annually but the cost of

the employees is in the order of $1,500/m^2. Consequently a readily achievable increase in productivity of 10% would produce a payback of about $150/m^2, a cost benefit approaching the entire lease cost of the office space. To-date this type of benefit has not been included in the economic analysis of high performance green buildings because the results have not been scientifically verified and also because the impact is so enormous. In general, for the economic advantages of green buildings to be fully evident, the use of Life-Cycle Costing (LCC) is essential. LCC readily demonstrates that the total cost of a building, its construction and operational costs, are lower for high performance buildings. Generally energy consumption is the driving force in LCC because it is most readily affected by building design, is readily quantifiable, and there are extensive simulation programs to help optimise energy measures *versus* costs. Broadened LCC that include water consumption, maintenance, and other operational costs should be used whenever adequate data exists.

8.3 Ecology as the Basis for Resource Efficient Design

To-date the green building concept has been slightly hampered by the lack of a philosophical and technical foundation that would give it a unifying theme and direction. In effect the definition of sustainable construction mentions what should most clearly provide this direction, that is, ecological principles. Unfortunately, it is the rare building professional, even one dedicated to green building, that has developed more than a very cursory knowledge of the science of ecology. In this section some of the basic ecological concepts that should be understood for resource efficient design are covered.

8.3.1 Ecological Concepts

Ecology is a science which involves the study of systems, specifically the study of the interactions of organisms, populations, and biological species (including humans) with their living and nonliving environment. The green building movement espouses that the built environment should be created using 'ecological' principles, yet there is little evidence that there is any real understanding of ecology or ecological principles on the part of the various protagonists in the building process. The reasons for this disconnection are fairly obvious. Foremost among these reasons is that the protagonists are generally designers, builders, managers, and investors with no environmental or ecological education or training. Consequently, although their intuition is that ecological literacy is an important aspect of creating a high performance built environment, adhering to ecological precepts is strictly by a 'seat of the pants' approach. A deeper understanding of ecology and ecological concepts is essential for a truly effective green building movement. Without it, these efforts are not much more than mere decor or window dressing.

Some have suggested that human industrial systems can and must use both the metaphor and actual behaviour of ecological systems as guidance for their design. Current industrial systems are the equivalent of ecosystem r-strategists (pioneer species) that rapidly colonise areas laid bare by fire or other natural catastrophes. Their strategy of maximum mobility and reproduction invests all their energy in seeds and rapid growth and minimises investments in structure. r-Strategists are mobile, surviving by being the first at the scene of a disturbance and securing resources before they are eroded away. However when the resource base has been expended, their populations will diminish to very low levels. They are not competitive in the long run and only excel at out competing each other in a loose 'scramble competition,' eventually losing out to better strategies. In natural succession, K-strategist species supplant r-strategist species because they spend less energy on generating seeds and more on systems such as roots that will enable their survival during periods of lower available resources. K-strategists live in synergy with surrounding species and are far more complex than the other r-strategists. K-strategists, unlike r-strategists, are not mobile but survive longer at higher density by developing highly efficient resource and energy feedback loops. K-strategists invest more in structure than mobility and this is the template around which their complex interrelationships efficiently conserve the flow of energy and resources. **Figure 8.2** depicts the r-K strategies and their cyclical nature [4].

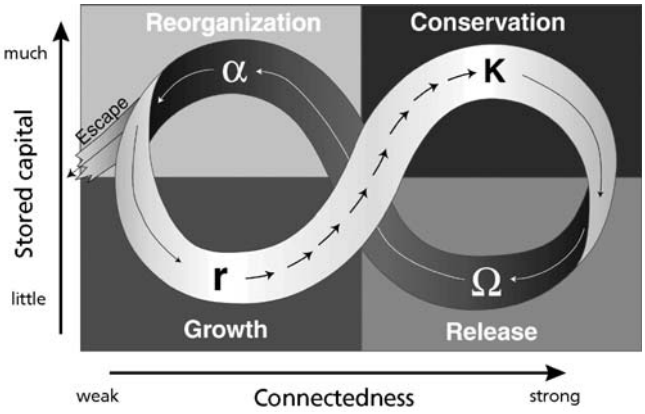

Figure 8.2 Ecological systems from the point of view of 'adaptive management'. Ecosystems have cyclic behaviour starting with a growth r-strategy in which energy is directed toward growth and reproduction, eventually shifting to a synergistic K-strategy in which species occupy specialised niches. Ecosystems are eventually upset and crash, (e.g., through disease or fire), moving rapidly through Ω- and α-stages back to a point where it can cycle back into its original system or exit into a totally new system (Escape in the diagram above). A forest can cycle through multiple iterations as a pine forest but exit into a state as a cypress swamp.

In a similar manner it could be said that industrial systems behave in a similar fashion. s-Strategist industries employ the typical industrial processes of today, linear systems with little or no recovery of materials from the waste stream. Closed-loop K-strategist industrial ecosystems with full materials recovery do not exist at present, partially due to a lack of technology and partially due to poor product design. It is only very recently that industrial products such as automobiles are being 'designed for the environment', that is designed for reusing or recycling of components and with full consideration of how to reduce the impacts on ecological systems. Today's r-strategist industrial system is simply a primitive stage in a process of never ending evolution of human designed systems that evolve in a manner similar to nature. The question for humankind emerging from this observation of nature is how to move as rapidly as possible from our r-strategy global economy to an advanced, closed materials cycle K-strategy.

The primary lesson the construction industry can learn from nature is to cycle its materials in a closed-loop manner, the goal being a 'zero waste' system. This could be achieved by designing all components from recyclable materials and for quick disassembly. For example, when its useful life has ended, an air handler in a large commercial building would be returned to its producer who would then be able to quickly separate all steel, copper, and aluminium components for recycling, compost the organic insulation, and essentially throw away nothing. Building structural elements would be designed to be unpinned or unscrewed rather than demolished in place. Integrated with a similarly functioning industrial system, builders and manufacturers of building materials and products would exchange resources with automobile industry, computer chip manufacturers, and consumer products on an as-needed basis. Today's building curtain wall system may be comprised largely of yesterday's washing machine, Ford transmission, and other artifacts, all designed as part of a larger human ecosystem.

The outcomes of applying these natural system analogues to construction would be a built environment:

(1) that is readily deconstructable at the end of its useful life;

(2) consists of components that are decoupled from the building for easy replacement;

(3) comprised of products that are themselves designed for recycling;

(4) whose bulk structural materials are recyclable;

(5) whose metabolism would be very slow due to its durability and adaptability; and

(6) that promotes health for its human occupants.

8.3.2 Industrial Ecology as a Starting Point

Perhaps the most serious and developed effort at applying ecological principles to human systems is industrial ecology. Industrial ecology can be defined as the application of ecological theory to industrial systems or the ecological restructuring of industry. In its implementation it addresses materials, institutional barriers, and regional strategies and experiments. Industrial metabolism is the flow of materials and energy through the industrial system and is directed at understanding the flows of materials and energy from human activities and the interaction of these flows with global biogeochemical cycles. The rejection of the concept of 'waste' is one of the most important outcomes of industrial ecology. In an ideal industrial system, nonrenewable materials would be utilised in a closed loop to minimise the input of virgin resources. Products degraded by age or service would be designed to be reverse-distributed back to industry for recycling or remanufacturing. The processes creating the loops would be designed for zero solid waste to include zero emissions to water and air. Renewable resources would also be used in a closed loop manner to the maximum extent possible and follow the same zero waste rules as for nonrenewables. Renewable resources, being biological in origin, could be recycled by natural processes as simple biomass which could serve as nourishment for biological growth.

According to Richards and Frosch [5], 'industrial ecology views environmental quality in terms of the interactions among and between units of production and consumption and their economic and natural environments, and it does so with a special focus on materials flows and energy use.' They also go on to note that the integration of environmental factors can occur at three scales:

- Microlevel (the industrial plant).
- Mesolevel (corporation or group operating as a system).
- Macrolevel (nation, region, world).

It is interesting to note that these three levels are identical to the levels at which natural systems are studied for their function.

Industrial ecology has evolved in several major directions since it became well-known in the late 1980s. The first direction is the evolution of the concept of eco-industrial parks (EIP) in which waste and by-products from a group of companies are shared as resources. Sometimes referred to as 'industrial symbiosis,' the grouping of industries with compatible energy and materials waste and needs helps minimise the emissions of the industrial cluster. Extending the concept of waste energy/materials sharing to regional scale can hypothetically result in 'islands of sustainability'. The Kalundborg EIP in Denmark is the most frequently cited success story of industrial symbiosis but detailed knowledge of the materials, energy, economic, environmental, and social effects of this industry cluster are not well-known.

The second major direction of industrial ecology is the optimisation of material flow by increasing resource productivity or dematerialisation. The notion of a service economy which sells services instead of the actual material products is considered the *sine qua non* of this strategy, alternatively referred to as 'systemic dematerialisation'. One of the questions facing industrial ecology is whether corporations can profit more from closing material loops and behaving environmentally responsibly or through built-in obsolescence and open material cycles.

8.3.3 Rules of the Production-Consumption System

For the system that produces the components for construction, the question remains as to how this system and, for that matter, the overall industrial system should behave if it is to follow ecological principles. James Kay, an ecologist and professor at the University of Waterloo, Ontario, Canada, suggests a set of rules for use in considering how to make the transition from today's industrial system, which would of course include the construction industry, to one that operates in concert rather than in conflict with ecosystems [2]. These four rules are:

(1) Interfacing: the interface between man-made systems and natural ecosystems should reflect the limited ability of natural ecosystems to provide energy and absorb waste before their survival potential is significantly altered, and that the survival potential natural ecosystems must be maintained.

(2) Bionics: the behaviour and structure of large-scale, man-made systems should be as similar as possible to those exhibited by natural ecosystems.

(3) Appropriate biotechnology: whenever feasible the function of a component of a man-made system should be carried out by a subsystem of the natural biosphere. This is referred to as using appropriate biotechnology.

(4) Renewable resources: non-renewable resources should be used only as capital expenditure to bring renewable resources on line.

8.3.4 The Golden Rules of Eco-Design

Stefan Bringezu of the Wuppertal Institute in Germany suggests an alternative set of rules for the industrial systems to follow in shifting course to one that adheres to ecological principles. He labels them the Golden Rules of Eco-Design and they are as follows [1]:

(1) Potential impacts to the environment should be considered on a life-cycle basis or from cradle-to-grave.

(2) The intensity of use of processes, products and services should be maximised.

(3) The intensity of resource use (materials, energy, and land) should be minimised.

(4) Hazardous substances should be eliminated.

(5) Resource input should be shifted towards renewables.

8.3.5 Construction Ecology

Clearly a new concept for materials and energy use in the construction industry is needed if sustainability is to be achieved. As noted at the start of this chapter, industrial systems in general are beginning to take the first steps towards examining their resource utilisation or metabolism, and beginning the process of defining and implementing industrial ecology. In this same spirit, a subset of these efforts for the construction industry would help accelerate the move toward integrating in with nature and behaving in a 'natural' manner. It is proposed that construction ecology be considered as the development and maintenance of a built environment:

(1) with a materials system that functions in a closed loop that is integrated with eco-industrial and natural systems;

(2) that depends solely on renewable energy sources, and

(3) that fosters preservation of natural system functions. Construction metabolism is resource utilisation in the built environment that mimics natural system's metabolism by recycling materials resources by using renewable energy systems. It would be a result of applying the general principles of industrial ecology and the specific dictates of construction ecology.

The outcomes of applying these natural system analogues to construction would be a built environment:

(1) That is readily deconstructable at the end of its useful life.

(2) Whose components are decoupled from the building for easy replacement.

(3) Comprised of products that are themselves designed for recycling.

(4) Whose bulk structural materials are recyclable.

(5) Whose metabolism would be very slow due to its durability and adaptability, and

(6) That promotes health for its human occupants.

8.4 Resource Efficiency Strategies for Building Design

Resource efficiency in general is well-recognised as a key issue for resolution in producing a new class of high performance buildings. Several new concepts have emerged in the past few years which are affecting how we look at resources in the light of sustainable development, among them Factor 4, Factor 10, and dematerialisation. Factor 4 proposed by the authors of the book of the same title suggests that we already have the technologies needed to create a 75% reduction in energy, water, and materials use [6]. Examples are compact disks for data storage, fibre optic cables for data transmission, and carbon fibre composites for automobile bodies. Each of these strategies reduces the need for materials by at least 75% for the purposes for which they were designed. A Factor 4 reduction in consumption of these resources would allow humanity to approach a condition approaching sustainability today. Over the long-term, however, a Factor 10 reduction in resource consumption will be needed to accommodate both the needs of the developing world as well as a slowly increasing total world population. Considering the materials issues, the general strategy is called 'dematerialisation'. For automobiles, computers, and many other human artifacts, this strategy makes sense, especially when coupled with increased recycling of materials. For the built environment, the option of dematerialisation of buildings is not so straightforward as the bulk of the built environment is comprised of high mass, low value materials such as concrete, aggregates, fill, and stone. The question then becomes one of how best to apply these materials to maximise their recycling potential.

8.4.1 Materials Selection and Design for Deconstruction

Selecting 'environmentally friendly' materials and products for construction is perhaps the most difficult challenge faced by design professionals today. It is difficult if not impossible to define a 'green' building material or product as so few exist today. Some qualities of one 'set' of ideal materials is that they are derived from renewable resources and recyclable in the sense that they can be composted and returned to nature as a nutrient. Clearly wood products, cotton, wool, jute, hemp, sisal, kenaf and many other materials have these qualities but they are not being recycled or composted in any meaningful way at present. Another set of ideal materials are derived from non-renewable

resources but are highly recyclable. Metals, plastics, glass, aggregates, and dirt all potentially have this property but it is only metals that actually have high rates of recycling. Assembling materials into more complex products creates another range of problems for recycling. Clearly products have to be designed for economic disassembly and comprise recyclable organic or inorganic materials to be considered truly green. It must also be kept in mind that thermodynamics limit the maximum rate of recycling, with the implication that what is not recycled will dissipate into the biosphere and potentially have effects on living systems.

That being said, it must also be acknowledged that we are in the midst of a transition that in some circles is being referred to as the post-industrial revolution. The shift to practices where resource efficiency is the norm rather than the exception is just beginning and there are only a small number of cases where appropriate use of materials can be demonstrated. Innovation coupled with appropriate policy instruments will be needed to complete the shift to practices that for all practical purposes eliminate the idea of waste. In this transitional era, materials selection involves various compromises. Environmental Building News (EBN), a US publisher of perhaps the most informative monthly journal on green building, suggested the order of approaching this problem. First, they suggest that materials selection follow the following priority with respect to life-cycle considerations:

1. Construction and use
2. Manufacturing
3. Raw materials acquisition and preparation
4. Disposal/reuse

The following are the steps EBN suggests for each of these four life-cycle phases.

Construction and use phase

Step 1: Energy use

Step 2: Occupant health

Step 3: Durability and maintenance

Manufacturing phase

Step 4: Hazardous by-products

Step 5: Energy use (in manufacturing)

Step 6: Manufacturing waste

Raw Materials acquisition and preparation phase

Step 7: Resources limitations

Step 8: Impacts of resource extraction

Step 9: Transportation

Disposal or reuse phase

Step 10: Demolition waste

Step 11: Hazardous materials from demolition

Step 12: Review the results

An examination of these phases and steps indicates that the authors propose that the performance of the materials is the foremost consideration, particularly when they affect the building's energy consumption. Impacts on ecosystems appear only in the bottom half of the list (Step 8) and consequently the application of ecology to construction in this approach is very weak. Nonetheless, we are in a state of change and hopefully impact on ecosystems will someday rise to the top of the list as innovation and policy instruments reshape priorities.

8.4.2 Energy Strategies

Buildings consume 30% of primary energy in the US and 40% in other industrialised countries. As indicated in the previous section, energy use remains the predominant concern of most advocates of high performance buildings and compromises in materials and systems are generally made to reduce energy use to the minimum. For example, insulation that has significant environmental impacts would be favoured if its energy conserving performance was significant. Its ability to be recycled or its impact on ecosystems would be minimal concerns compared to the quantity of energy consumed. For minimising energy use in buildings, the following are the priorities for consideration:

(1) ***Passive design***: Ensure the building 'defaults to nature,' that is, that it is able to function reasonably well and be used for its intended purpose even if it were to be cut off from the grid. Passive design uses the building's geometry, materials, mass, compass orientation and the site's natural resources and microclimate to provide heating, cooling, lighting, and ventilation with minimal reliance on manufactured mechanical or electrical components.

(2) ***Envelope design***: Ensure the envelope (walls, roof, floor, windows, and doors) provide a tight, highly thermally resistant skin for the building such that ventilation is easily controllable.

(3) ***Active system design***: Design the mechanical and electrical components of the building's services to maximise efficiency and minimise losses. This includes selecting equipment, motors, and lighting to maximise their efficiency and designing ductwork and piping to minimise energy for moving air and other fluids. Control systems are an important component of active design. Occupancy sensors can be used to turn lighting on/off depending on room use. Throttling sensors can reduce lighting energy use to the exact level needed to supplement natural lighting. Other sensors and their associated computers can control outdoor ventilation.

(4) ***Device selection***: Selectors of appliances, computers, and other energy consuming devices should pay close attention to minimising energy consumption. The US Environmental Protection Agency (EPA) Energy Star program provides a label for computers, monitors, fax machines, and copy machines that can go into 'sleep' mode. However it does not address total energy consumption. Consequently owners or tenants need to become more sophisticated when selecting equipment to complete the outfitting of a building.

(5) ***Energy source selection***: In light of sustainability, renewable energy systems have priority for supplying energy to the built environment. Two basic approaches can be followed. First, renewable energy systems such as photovoltaics can be part of the building design and construction and incorporated into the building project. Second, energy from renewable resources can be procured from so-called 'green' power companies, that is, electrical utilities that generate electricity from wind, solar energy, or by hydropower.

It should be noted that the design of energy systems in this manner is an iterative process. Passive and envelope design will affect building loads and consequently the size of mechanical and electrical systems. The passive ventilation strategy may involve operable windows and therefore affect the building's envelope. With respect to goals for energy use in buildings, a Factor 10 reduction in building energy use in the US would bring the current annual average consumption of about 290 kwh/m^2 down to about 29 kwh/m^2. A current state-of-the-art classroom building at the University of Florida in Gainesville, Florida, following the most recent US Green Building Council LEED building assessment standard is predicted to consume 179 kwh/m^2 annually, a significant improvement over average consumption but a far cry away from the Factor 10 reduction in energy consumption that is proposed as the road to sustainability. Conventional approaches to energy conservation clearly will not work and some radical changes are needed to create a resource efficient building. These include intensive simulation, rediscovering passive design, a flexible comfort zone, and detailed integration of landscaping into the building proper.

8.4.3 Water, Wastewater and Stormwater

Water is probably the limiting resource for development in most areas of the world. Of the hydrological cycle's vast quantity of water, only 2% is potable and only a small percentage of potable water is accessible. The earth's surface is 70% water but only 2.5% of this is freshwater and only 0.007% of the earth's freshwater resources are accessible for human use. Consequently water is a very precious resource in relatively short supply in most locations worldwide. In the US water consumption in homes is at a rate of about 380 litres per person daily and half of that is attributed to landscape irrigation. Current technology provides fixtures with relatively low flow characteristics:

Toilets:	6 litres/flush
Urinals:	3.8 litres/flush
Showerheads:	9.5 litres/minute
Taps:	8.3 litres/minute

Water consumption by landscaping can be dramatically reduced through appropriate plant selection and use of low flow or trickle irrigation systems. The use of extravagant areas of turf grass is a serious problem in that it requires not only substantial irrigation but also high maintenance and the use of pesticides, herbicides, and fertiliser.

Several other techniques are emerging or re-emerging in today's green buildings. Rainwater harvesting or the use of cisterns provides for the collection and use of rainwater for non-potable uses such as fixture flushing and landscape irrigation. Greywater systems or the recycling of water uncontaminated by human waste, e.g., from sinks, lavatories, clothes washing machines, is a practical reality for recovering water for reuse.

8.4.4 Land Use

The reuse of land that has seen prior human use as industrial or urban areas is an important resource conservation strategy that is complex and difficult to include in planning and shaping the future built environment. It is however a matter of the highest importance because of the role of land in providing ecological capacity, environmental amenity, biodiversity and food production. Brownfields or grayfields, the former land that has been contaminated by human activities, the latter land that has been built on in the past (for example, a shopping centre), should both have high priority for reuse. Greenfields, that is land that has not previously been built upon, needs to be protected for its ecological and biological value to the maximum extent possible.

8.4.5 Landscape as a Resource

The final resource considered here is landscape. In the context of this chapter, landscape refers to the biological species that are deliberately integrated with the built environment, whether they exist on site or are imported to the site. At this point in the evolution of green buildings, landscaping is an highly underrated and under-utilised resource. Trees and other plants can provide shading for buildings, reducing direct solar insolation on the building as well as reducing the local air temperature. In temperate climates, many species of trees shed their foliage and allow sunlight to pass through their branches, providing solar access for heating.

The role of trees in contending with stormwater is an important and largely overlooked benefit of landscaping. A study by American Forests (*www.americanforests.org*), for example, showed that the loss of trees in the Atlanta metropolitan area from 1986 to 1993 had increased stormwater runoff on over 202,350 hectares in that region, and the cost of stormwater structures to handle the excess stormwater was estimated at $2 billion. Trees and other landscaping can provide both significant stormwater and flood control benefits. Trees and forests also provide clean water and act as natural reservoirs, providing clean water and protecting watersheds.

Landscaping also provides environmental amenities, improving the area surrounding a building, and improving its value. Landscaping and green space is also connected to human well-being and to the productivity of a work force. Landscape also provides habitat for all types of species and planting trees also helps offset the ever increasing 'carbon debt'.

8.5 Case Study

The following case study covers the production of products and an approach to the resource efficiency strategy evolving in a typical construction products supply sector, in this case, the US carpet tile industry. It discusses both technical and policy approaches that can be taken to create a resource-efficient product.

Perhaps the industry most approaching the ideals of a true ecology of construction in the US is the carpet tile industry. Carpet tiles are semi-rigid squares (typically 450 mm per side) of carpet that are used in commercial and industrial applications. The advantage of this carpeting system is that areas of carpet that have become worn out due to heavy traffic or damage can be simply removed and replaced with new carpet tiles. For a variety of reasons several major manufacturers of carpet tiles are competing for market share based, at least partially, on the recyclability of their products. Among these manufacturers

are Interface, Collins & Aikman, and Milliken. Each of these manufacturers has evolved a different strategy for competing in this age of emerging awareness of greening issues.

Interface recently released information about a new product called Solenium which is a hybrid carpet-resilient flooring material. Although it is a composite of several different layers of materials polytrimethylene terephthalate (PTT) face fibre, fibreglass and carbite adhesive, polyurethane cushion, and polypropylene secondary backing, it is designed for disassembly. At about 190 °C, the adhesive bonding between the face fibre and urethane cushion dissociates, allowing the materials to be peeled apart for recycling. The secondary backing can be manually peeled away from the urethane cushion. Although the new product does require some virgin materials for its manufacture, the bulk of the materials can be recycled into new product. Interface also offers materials such as Solenium as 'Products of Service', meaning that they can be leased from Interface who then take on the responsibility for maintaining, removing worn sections, and recycling the used materials into new products.

Backing materials are one of the most important components of carpeting because they come into contact with the underlying surface and must have adequate toughness, strength, and durability to withstand the wide variety of loads to which they will be subjected. Collins & Aikman created a new backing material which they refer to as Powerbond ER3 and which contains up to 50% post-consumer waste in the form of old carpet from its competitors. The remainder of the ER3 product is internal production waste and post-industrial automotive waste. The manufacturer claims that the ER3 backing may in fact be superior to backing it manufactures made of 100% virgin materials.

Milliken's approach to effective materials use is to remanufacture used carpeting by deep cleaning, retexturing the surface and overprinting a new pattern on top of the old colour. As part of their marketing strategy, Milliken is planning on selling a product called 'Precycle' which indicates the carpet tiles are designed for remanufacture and with an eye to potential colour schemes for future generations of remanufactured product. Remanufactured carpeting also carries a significant financial incentive – the cost of the remanufactured version is half that of the new carpet tiles.

Raw materials manufacturers such as Dupont, AlliedSignal, BASF, and DSM Chemicals are also participating in related closed loop materials ventures. In a new venture called Evergreen Nylon Recycling, Allied Signal and DSM are building a facility which recycles a variety of polyamide called Nylon 6, which is highly recyclable. In effect the recycled polymer is identical to the virgin polymer and thus 100% recyclable. A process known as selective pyrolysis uses heat and steam to separate the constituent products of the Nylon carpet, and caprolactam, the building block of Nylon 6, rises to the top of the

vat during processing. To assist with identifying carpet containing Nylon 6 and to prevent contamination from other types of Nylon carpeting, AlliedSignal developed a hand-held infrared device to assist contractors in the collection of the appropriate used carpeting in the field.

These actions and strategic moves by carpet tile manufacturers and raw materials producers for the carpet industry are perhaps the most comprehensive example of the evolution of a construction ecology that has similarities to its natural system counterpart. For the first time, manufacturers are actually competing not only on the function and cost of their products, but also on the ability of the materials to be kept in a closed loop system of manufacture-use-recovery-manufacture. The question that emerges from this observation of this one segment of construction materials is: when can we expect to see similar progress in other product segments, for example wall panels or acoustic tiles? The carpet tile industry is providing ample evidence that systems approaching the ideals of construction ecology are both achievable and profitable.

The flooring industry is an anomaly in that the industry has moved towards waste minimisation of its own volition without regulatory incentive. However, in other industries, the voluntary adoption of life-cycle analysis is unlikely to occur without some regulation and incentives. Therefore, in order to use the lessons learned from the carpet and flooring industry regarding the possible innovation in life-cycle approaches to products that result in waste minimisation, a framework has been designed using Hasegawa's scheme for classifying policy instruments. In the case of carpet tiles, the consumer would be the carpet subcontractor who purchases and installs the tiles. The following paragraphs address the various policy instrument possibilities by phase of the built environment.

8.5.1 Design and Construction

Producers could be required by regulation to take life-cycle responsibility for their products, thus designing them for recycling, using Design for the Environment principles, or to use recyclable materials in their products. This could include a scheme similar to Extended Producer Responsibility (EPR) in which the producer is required to take back both used and waste products they had manufactured. For the consumer or builder, a requirement that buildings must contain a certain minimum percentage of recycled content and recyclable materials would be in order. Producers could also be required to use specific materials for specific products if technical data indicated that these materials were in fact recyclable where the alternatives were not. Economic incentives for improved materials use behaviour could include taxes on virgin materials and subsidies for using recycled materials. It is important to pair incentives and disincentives

together across the life-cycle of a specific product to ensure waste minimisation across the board for existing products as well as new products. To assist the impacts of regulatory and economic instruments, Eco-Labelling and Certification schemes could assist in providing information about products that meet the highest standards for materials recycling and recyclability.

8.5.2 Use and Refurbishment

Carpet tiles are one of the shorter lived products of the built environment, requiring replacement in as little as five years in heavily trafficked areas such as corridors. It could well occur that carpet tiles are replaced eight to ten times over the life-cycle of a 50 year building. Consequently carpet tiles must be designed for easy removal and replacement to minimise their impacts. Keeping carpet tile waste out of landfills has to be a primary objective of policy instruments at this stage of the building cycle. The general rules would be for contractors to be required to extract used carpet tiles and return them to the manufacturer or in fact any manufacturer for refurbishment and/or recycling. When replacing materials, the same incentives and disincentives that exist at the construction stage would occur once again. Closing material loops must also include incentives to set up the logistics of moving materials from tens of thousands of building sites back to the manufacturer. In the case of Interface, their strategy is to create products of service, for example through their Evergreen Lease programme in which they retain ownership of the carpet tiles while leasing the service of the carpet tiles to the user. A similar strategy could be used for many building components, with the manufacturers retaining both ownership and responsibility for building products. This type of activity could be encouraged via economic instruments that would provide tax credits for products of service utilised in buildings.

8.5.3 Demolition/End Use

Demolition waste comprises the bulk of the construction and demolition waste stream from construction. In the US, of the approximately 145 million metric tonnes construction and demolition waste, 92% of this waste stream is connected to demolition activities. For products to be returned to their manufacturers for use as raw materials for new products, it is necessary to insure that the removed materials are as clean as possible in order to maximise the 'recycling potential' of the waste materials. This generally implies an orderly process of buildings disassembly, that is a process of 'deconstruction' rather than demolition in which the materials of the former building are all commingled. Consequently policy instruments that require deliberate disassembly of buildings are needed to insure materials are removed in as high quality a condition as possible. With respect to regulatory instruments, the primary instruments would require two actions:

(1) the storage of disassembly information in the building, and

(2) the provision of adequate time in the permitting process to allow building disassembly.

The latter could be implemented by requiring delay times after application for a building demolition permit. Economic instruments for this phase would include increasing the cost of disposal of demolition waste and providing incentives, perhaps in the form of subsidies, for entities that set up deconstruction, recycling, and/or materials reuse businesses. Information instruments could include Eco-Labelling schemes that have as one of their criteria the ability to disassemble products into recyclable materials.

8.6 Conclusions

Resource efficient design of the built environment is a very complex undertaking. Buildings are historical and cultural artifacts as well as in some cases being works of art. Their evolution in the industrial age has made them fairly difficult to alter in the emerging post-industrial, information and service driven world. Shifts in thinking and practice need to take place at several levels in order to create a truly resource efficient, built environment. Industries engaged in manufacturing building products have to create components that are able to be reused or readily recycled. They have to utilise technology to create energy systems based on renewable energy and that consume minimal energy. Materials of building components need to be of high value which motivates their recycling. It stands to reason that these materials need to be easily extractable from these components to facilitate their recycling. Water use can be squeezed even further through rainwater harvesting and water recycling as well as continuing to reduce the consumption profile of plumbing profiles and landscaping. Land must be used wisely and preserved for amenity, biological function, and for food production. We also have much to learn about the use of landscaping integrated with the built environment. Finally we have to make the transition in building design from guessing about how to create a sustainable built environment to truly using deep ecological design and the understanding of ecology in the design process. When we are able to achieve this, we will be able to properly claim we are engaged in resource efficient design.

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9 Processing of Individual Plastics Components for House Construction, for Civil and Highway Engineering Applications

Leyla Aras and Guneri Akovali

9.1 Processing of Plastics

Polymer processing is very much dependent on the rheological properties of the polymer in question. An important consideration should be whether the material is thermoplastic or thermosetting. The other important considerations are the softening temperature, thermal stability and the size and shape of the end product. Methods of processing polymers have several elementary steps in common, i.e., handling of particulate solids, melting pressurisation and pumping, mixing, and final steps of devolatilisation and stripping off undesired components [1].

Polymer processing operations may be classified as:

1. Extrusion
2. Moulding
3. Spinning
4. Calendering
5. Coating

9.1.1 Extrusion

This is the most widely used processing method for plastics and its applications include the continuous production of plastic pipe, sheet and rods. As shown in **Figure 9.1**, in the extrusion process, polymer is propelled continuously along a screw through regions of high temperature and pressure where it is melted and compacted and finally forced through a die shaped to give the final object [2]. The main components of an extruder as shown in the figure are the extruder and the die. The extruder barrel is divided into three sections. The first section is called the feed, picks up the finally divided (in the form of small pellets or powder) polymer from a hopper and propels it into the extruder cylinder. The polymer is heated by the electrical heaters attached and molten polymer is now in the second section called the compression zone. By the time the resin reaches the third section,

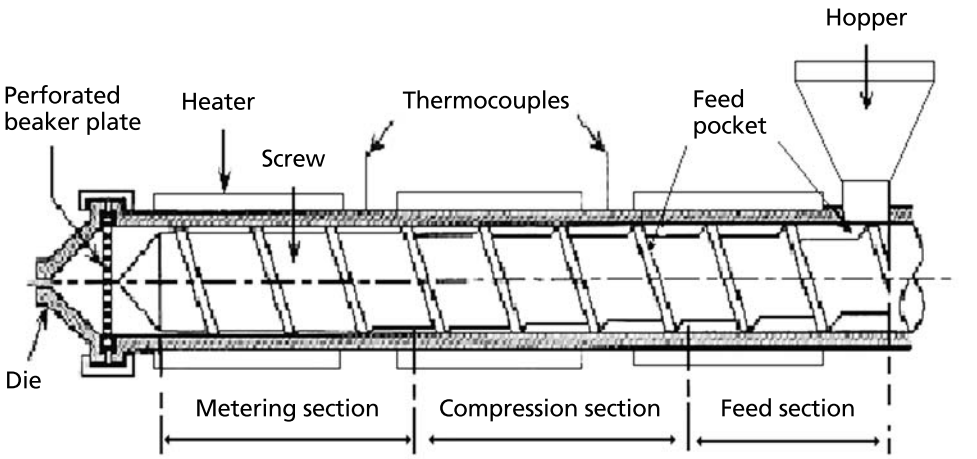

Figure 9.1 Illustration of a single-screw plasticating extruder

the metering zone, all the resin has melted and the shearing action of the screw rotating against the inner wall of the extruder barrel forces the melt out of the extruder and through a die. The die can be of several shapes, i.e., it can be in the form of an annulus for extruding pipe, it can be a capillary die to extrude rods, or a slit die having a rectangular opening to extrude sheet. A specially designed capillary die is used to coat wire with a layer of plastic insulation, [3].

In commercial polymer production, devolatilisation is also carried out through an opening for venting volatile products.

Films and sheets consisting of layers of two or more different polymers can be produced by mixing the molten streams from a similar number of extruders in a multi-manifold die. By this process, it is possible to combine materials to provide combinations of properties that cannot be obtained in a single polymer.

The extrusion of film can also be carried out by casting, as in sheet extrusion or by the blown film process.

In the construction industry, extrusion is used to produce:

- Pipes such as polyethylene (PE) and rigid polyvinyl chloride (PVC), pressure pipes in chemical plant.
- Rigid PVC or acrylonitrile-butadiene-styrene (ABS) tubes for plumbing.

- PE, PVC or other polymer films for green houses.
- Profiles, such as gaskets and sealing strips (from plasticised PVC and ethylene-vinyl acetate copolymer), hollow section fencing, window frames, architraves, skirting boards, and curtain rails from rigid PVC.
- Flat sheet such as ABS and toughened polystyrene (PS) sheet for subsequent thermoforming into hulls and dairy product containers, respectively.
- Corrugated sheet in translucent PVC for roof lights.
- Wire cable covering
- Thermoplastic polyester films for decorative, electrical and drawing use in offices.

9.1.2 Moulding

In the moulding process, finely divided plastic is forced by the application of heat and pressure to flow into, fill, and conform to the shape of a cavity (mould). Moulding can be carried out in several ways.

9.1.2.1 Compression Moulding

In compression moulding, the polymer is put between stationary and movable members of a mould. Under heat and pressure the material becomes plastic, flows to fill the mould and becomes homogeneous. Thermal and rheological properties of the polymer determines the necessary pressure and temperature, which typically is 150 °C and 6.9-20.7 MPa. A slight excess of material is placed in the mould to ensure its being completely filled.

9.1.2.2 Injection Moulding

Most thermoplastic materials are moulded by the process of injection moulding. In this process, the polymer is heated in a cylindrical chamber to a temperature at which it will flow and then it is forced in to a relatively cold, closed mould cavity by means of hydrolytically applied high pressure through a plunger or ram, but recently by means of a reciprocating screw that serves the dual purpose of providing the molten polymer mass and forcing it into the mould. The particulate polymer is picked up by the rotation of the screw, compressed and melted, the melt is mixed, and delivered to the entrance of the mould. The screw then moves forward to force a fixed volume of the molten polymer

into the closed mould. Melt temperature and pressure may be higher than those for compression moulding. The screw rotates and moves backward to ready the charge of polymer for the next cycle after the polymer melt has solidified in the cold mould. The speed of this type of moulding is very high.

9.1.2.2 Reaction Injection Moulding (RIM)

This is a relatively new process developed in Germany during late 1960s. The polymer is simultaneously synthesised and moulded into the finished product. Stoichiometric quantities of monomers (including catalysts and other additives) are placed into a mixing unit and rapidly forced into the mould where polymerisation occurs. The polymerisation reactions must be rapid enough to let cycle times be short. Temperatures and pressures in the RIM process are relatively lower than injection moulding. RIM has other advantages such as low energy consumption, rapid start up time, and it is suitable for the manufacture of large articles. RIM is suitable only for condensation type polymerisation kinetics.

Examples of polymers that can be processed by RIM are:

- Polyamides
- Epoxides
- Polyurethanes (PU) (approximately 95% of PU is produced by RIM)

If short fibres or fillers are introduced into the mould, the process is called reinforced reaction injection moulding (RRIM).

Both RIM and RRIM are particularly suited for the production of large parts.

Some additional information on this topic is provided in Section 9.2.1.2.

9.1.2.3 Spinning

Spinning is a process by which bulk polymer is converted to fibre form and this process requires solution and melting of the polymer. There are three spinning processes [4]:

1. Melt spinning
2. Dry spinning
3. Wet spinning

The three processes have many features in common. The conversion of the spun polymer melt or solution to a solid fibre involves cooking, solvent evaporation or coagulation depending on the spinning type used. Cooling of a fine filament is generally very rapid; solvent evaporation involves simultaneous outward mass transfer and inward heat transfer while coagulation involves both of the two-way mass transfers.

9.1.2.4 Calendering

Calendering, as shown in **Figure 9.2**, is a process which produces plastic sheets or films continuously. Thick sheet or granular resin is passed between pairs of highly polished heated rolls under high pressure. Precise control of roll temperature, pressure and speed of rotation are required for proper calendering. A large proportion of the resin used in calendering is PVC.

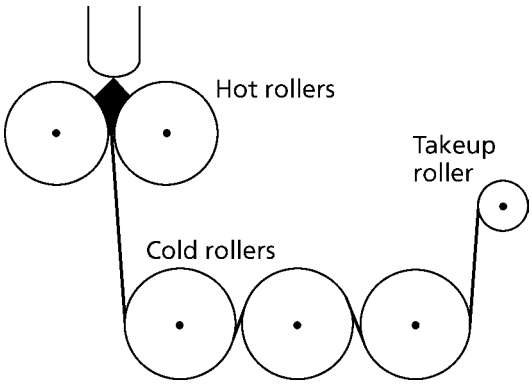

Figure 9.2. Generalised calendering process

9.1.2.5 Coating

The technology of coating fabrics and paper is a complex process and many different types of processes can be used to coat a thin layer of liquid onto a moving sheet called the web. Examples of coatings include the deposition of photographic emulsion on a cellular web, production of a magnetic surface on poly(ethyleneterephthalate) for recording and computer tape, polymer layer on a metal for capacitor applications, and finishes and backings on textile fibres and fabrics.

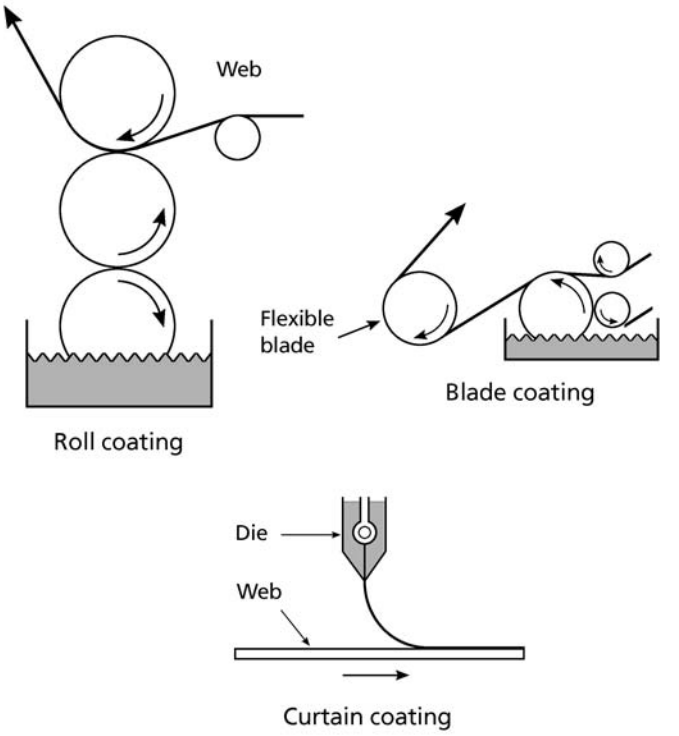

Figure 9.3 Examples of coating processes

Different coating operations are roll coating, blade coating, and curtain coating, which are shown in **Figure 9.3**.

9.2 Processing of Plastics Composites

Manufacturing techniques of plastic composites can be divided into two parts: processing of thermoplastics and thermosetting composites. There are certainly similarities between the processing of plastics (outlined in the previous section) and plastics composites, as well as between the processing of thermoplastics and thermosetting composites. For this reason, and to avoid duplication, whenever a different technique is involved for any one of them, it will be noted.

And since most of the plastic composites used in construction are of fibre reinforced thermosets, these will be emphasised in discussions.

9.2.1 Processing of (Fibre Reinforced) Thermoset Plastic Composites

In composite processing, the fibres and the resin mixture (with catalyst, etc.), is pressed first into the required shape and size (in the mould), then the system is left to cure to become permanently hardened.

Fibre reinforced (FR) thermoset plastic composites can be processed in the following different ways, depending on differences in the processing:

(a) manual processing (hand lay-up, spray-up, pressure bag and autoclave moulding),

(b) semi-automatic processing (cold pressing, compression moulding and resin injection),

(c) automatic processing (pultrusion, filament winding and injection moulding).

On the other hand, their processing can also be classified as follows:

(i) Open mould processing where there is only one mould involved and the material is in contact with the mould on one surface only. This technique is widely used in civil engineering applications

(ii) Closed mould processing, also called matched die processing, where the product is formed within a closed space of two moulds, i.e., with the conventional male-female mould. This technique is not usually used for the production of materials involved in construction industry [5].

Open mould processes are operated manually, with one exception (filament winding); while closed mould processes are either semi-automatic or completely automatic (**Figure 9.4**).

9.2.1.1 Open Mould Processes

In open mould processes (also called 'contact lamination' or 'contact moulding', there is a single positive, or a single negative, mould surface (usually with a large surface) on which starting materials (resins – commonly unsaturated polyesters and epoxies, fibres – usually either chopped or continuous glass fibres or mats, woven rovings and yarns or prepregs) are applied in layers to the desired thicknesses. This step is then followed by curing and removal of the part. In this process, there is no pressure application (or relatively little pressure in some cases) during the curing cycle.

Depending on the differences used in the application methods of layers and curing details, there are different open mould processes (such as hand lay-up, spray-up, automated laying

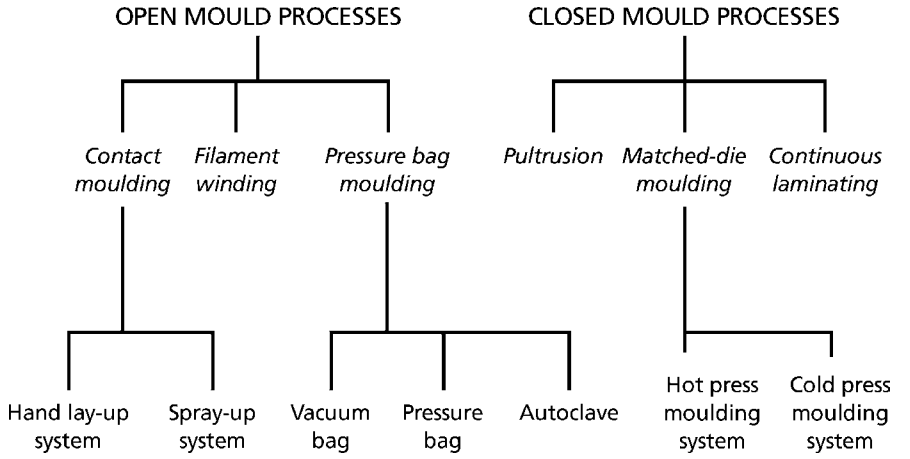

Figure 9.4 General processing diagram for reinforced thermosetting plastics composites

and spraying, bag moulding and autoclave moulding); two or more of which can be combined. Economy and design flexibilities provided by the process are the main advantages, (i.e., large and complex items can be produced easily), whereas, the process is labour intensive and gives rise to parts with only one finished surface. As mentioned previously, filament winding is an automated open mould process without having the disadvantages noted before.

Hand lay-up is a wet process and it is the simplest yet most labour-intensive and the most commonly used technique, since the 1940s. It is most suited for the production of similar components in limited numbers, (i.e., fibre-reinforced plastic (FRP) infill panels). In this method, successive layers of resin and reinforcement, (i.e., rovings, fabric, mat or randomly arranged chopped fibres of glass), are manually applied to an open mould, with the following basic procedure of five steps:

(i) cleaning and treatment of the mould with release agent(s),

(ii) application of a thin gel coat (of approximately 0.35 mm thick resin, possibly coloured; used to protect glass fibres (GF) from external effects including moisture and to provide a smooth finish). The gel coat applied face will be the finished surface part. If quality of surface finish is very important, the gel coat layer is applied with a spray gun.

(iii) application of successive layers of resin and GF, as soon as the gel coat has partially set. GF is usually used in the form of mat or cloth, and each layer is rolled carefully to remove possible air bubbles and to fully impregnate the fibre with the resin.

(iv) curing the part, and

(v) removing the fully hardened part from the mould and trimming the outside edges to size.

This method is preferred for relatively short production runs and large size objects.

'Hand lay-up with brush' method is used mostly for very low volume scale manufacturing and in general, the parts processed are considerably larger in size. In addition to production of huge boat hulls, this technique is also used to produce swimming pools, large container tanks, stage props, radomes and other formed sheets.

Most manufacturers use spray guns and pumping systems to have a more rapid and consistent mix to wet out the laminate, where highly accurate metering systems can also be used; and automated tape-laying machines have been developed recently, as discussed in the part on spray-up techniques.

Hand lay-up technique is also used for construction of highway bridges. For example the glass fibre reinforced plastic (GFRP) bridge in Bulgaria (with a 10 m span constructed in 1983), and the Miyun Bridge which is under construction in Beijing, China.

Hand lay-up for retrofitting (rehabilitation) is used in the construction industry to strengthen and upgrade the structures in flexure and shear (by retrofitting the material to their tensile and shear faces, where the surface of the structure, such as concrete steel, forms the mould for the composite). A number of different applications can be cited for hand lay-up for retrofitting (rehabilitation), such as: the confinement of concrete columns with composite sheets or plates bonded to them, the use of polymer composite plates for the flexural and shear strengthening of beams and slabs, wrapping of reinforced concrete structural elements for corrosion protection and durability of repairs. There are a number of examples for retrofitting of concrete bridges, (i.e., by using pultruded plates to upgrade for higher load capacities *in situ*) [5].

The hand lay-up technique is presented schematically in **Figure 9.5**.

Spray-up is a less labour intensive process than hand lay-up, and it is an another way to mechanise the application of resin-fibre layers and to reduce the time needed for the process. In this technique, liquid resin and chopped GF are simultaneously sprayed and deposited onto the open mould. Continuous rovings are chopped in the spray gun (to fibres of 25-75 mm length) and are added to the resin stream as it exits the nozzle. Spray guns are either: internal mix with air, airless internal mix, external mix with air, or airless external mix. The technique requires considerable operator skill if operated manually (for control of the thickness of the composite and to maintain a consistent polymer/glass ratio), however, the tooling costs are not too high. Spraying can also be

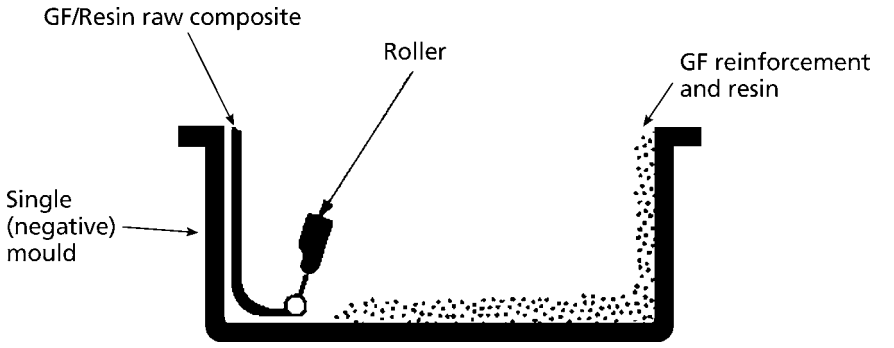

Figure 9.5 Hand lay-up moulding method

done automatically where the path of the spray gun is pre-programmed and computer controlled and is attached to an operator controlled machine or operated by a robot. To avoid possible volatile hazardous emissions, it is advantageous to use automated spray-up machines that can operate in sealed-off areas.

The spray-up technique is presented schematically in **Figure 9.6**.

Bag moulding processes use pressure applied to uncured resins on the mould in order to compact the laminates and to drive out volatiles. It can be in two different forms: vacuum bag or pressure bag moulding. Either of these can be used to supplement curing in the lay-up or spray-up processes.

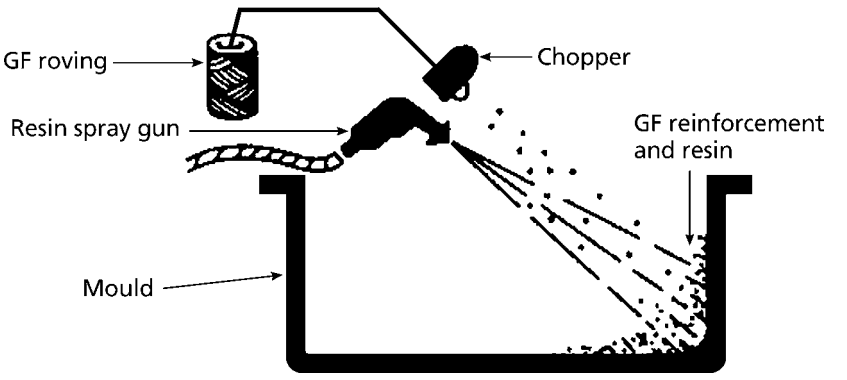

Figure 9.6 Spray-up moulding method

In vacuum bag moulding, a flexible non-adhering plastic [polyvinyl alcohol (PVA) or Nylon] sheet is used that covers the part after the lay-up or spray-up steps, and a vacuum is drawn to press the bag against the laminated part during curing, after the edges are sealed (**Figure 9.7a**). Vacuum bag moulding provides high reinforcement concentrations and better adhesion between the layers. Heat is often used to accelerate curing.

In pressure bag moulding, a positive air pressure (of several atmospheres) is used to inflate an elastomeric bag against the part while curing proceeds, which is mostly used for complex hollow shaped parts. Heat is often used to accelerate curing (**Figure 9.7b**).

Vacuum bag moulding for retrofitting is a semi-automatic resin infusion under flexible tooling (RIFT) technique, which allows production of quality composites. In the RIFT process, dry GF are pre-formed in a mould and are taken to the side and attached to the structure. A resin supply is then channelled to the prepreg, and both are enveloped in a vacuum bag. The flow of resin into dry GF (preform) develops the composite material and the adhesive bond between composite and structure as well.

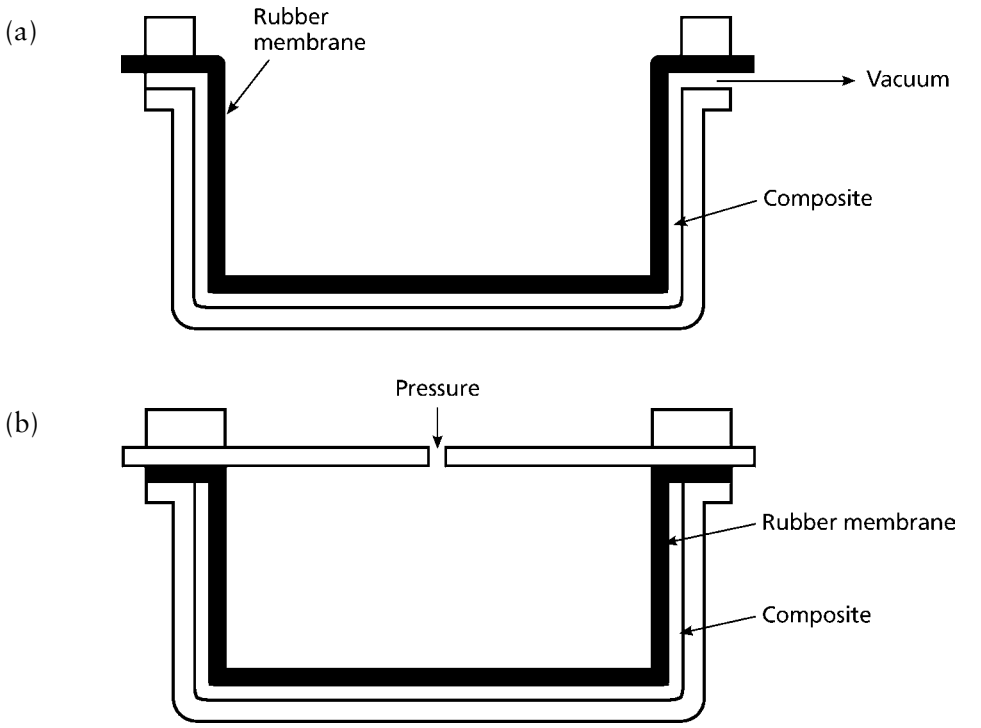

Figure 9.7 Moulding techniques: (a) Vacuum bag, (b) Pressure bag

Seismic retrofitting to columns uses filament winding of prepreg (pre impregnated) carbon fibres to produce a jacket which is then upgradable as described previously.

Autoclave moulding is a modification of the pressure bag method. It is used to produce high quality composites, (i.e., for aerospace applications), where high pressures (up to 0.6 MPa) and high temperatures (up to 700 °C) are used. An autoclave is a pressure vessel inside which the curing reaction occurs. With this process, it is possible to produce composite structures with up to 70 wt% GF reinforcements [5]. However, the autoclave process is rather costly.

Filament winding is a completely automatic open mould process. The process uses continuous strands of GF or carbon fibres applied with one of two common techniques: helical winding or polar winding. Helical winding is mostly used for high strength pipe type structures production, including sewage pipes; whereas polar winding is applied for pressure vessels.

In this technique, continuous reinforcements are fed through a transversing bath of activated resin and the polymer produced is then wound onto a rotating mandrel. Products with large structural shapes and with high circumferential and longitudinal mechanical strengths can be successfully produced by this technique. Since the filaments can be oriented with any desired controlled angle and that continuous reinforcements can be applied to very high levels, highly efficient products with maximum strength to weight ratios with good uniformities are obtained by filament winding [6] (**Figure 9.8**).

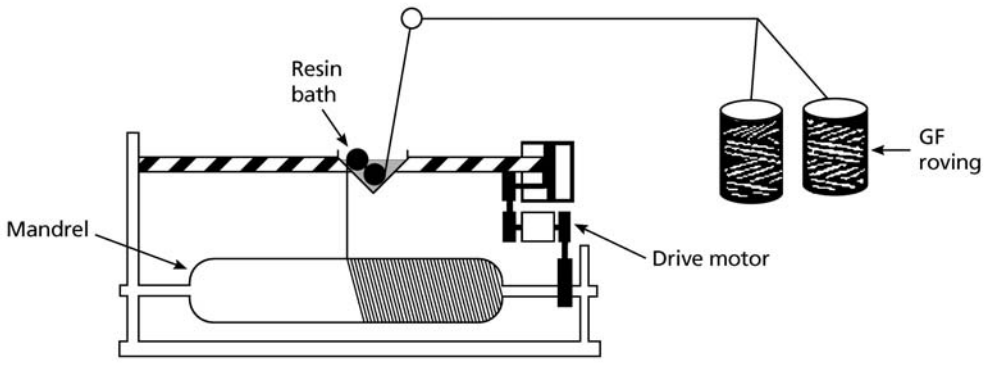

Figure 9.8 Filament winding

9.2.1.2 Closed Mould (Matched-Die Moulding) Processes

Closed mould (or matched-die moulding) processes are used in the composites industry for fabrication and manufacturing of three dimensional compounds and products. There are different closed moulding processes. Within these, there are: transfer moulding, compression moulding, resin injection moulding, injection moulding, pultrusion and extrusion.

Transfer moulding (or resin transfer moulding (RTM), plunger moulding) involves direct transference of a pre-determined amount of molten resin from reservoir, forced by a plunger through a small opening into the heated mould, where curing takes place (**Figure 9.9**). In this process, the mould is closed before the entry of the resin.

In the case of moulding thermosets, the uncured (initial) compound is usually placed first in the cavity of the mould, or the transfer pot of a transfer moulding process, and heated (to about 150 °C) to provide sufficient flow for mould filling. Pressure (approximately 13 MPa) is then applied for sufficient time to allow the resin to cure.

RTM is a reactive processing method where mould construction and clamping forces are simple and low, respectively. It is an ideal technique for production of strong and rigid parts with intricate geometries in medium scale production (tens of thousands). Mainly epoxy- and polyester-based resins, in addition to high service temperature bismaleimides

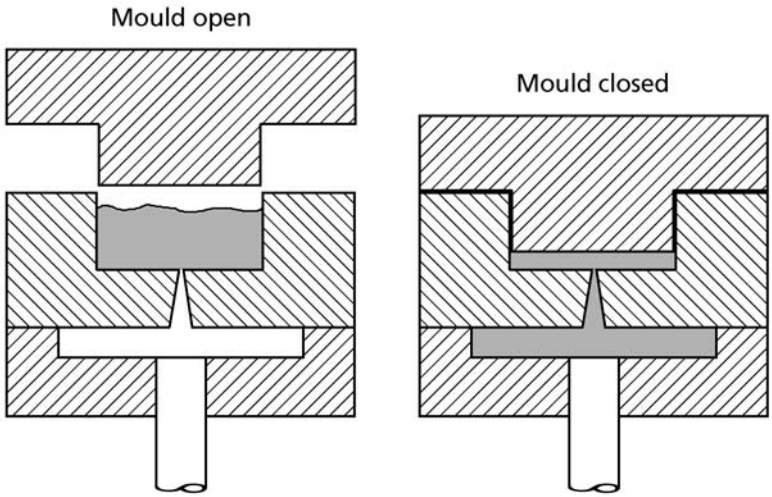

Figure 9.9 Transfer moulding. Molten resin transferred to the heated mould (left) followed by closing the mould and curing (right).

(BMI, approximately 180 °C), as well as phenolics and fast cured vinyl ester resins are processed by RTM.

Moulding compounds (MC) or 'pre-placed layers of fabrics' can be processed by this technique and for the latter, a subsequent stage resin is introduced into the mould by pressure and/or vacuum.

Some specific RTM methods, such as Assisted RTM (ARTM) and Thermal Expansion RTM (TERTN) are recognised as cost-effective techniques. In RTM, the compound is placed in a heated mould – where the temperature is between 120 and 150 °C – or a cold three-dimensional mould. When the mould is closed and pressure is applied (between 100 kPa and 15 MPa), the compound flows and fills the mould cavity(ies), while curing is taking place. Application of heat increases the rate and the extent of the cure.

Compression moulding is one of the least expensive and the simplest methods, which uses a certain amount of premixed compound placed in a heated three-dimensional mould, between stationary and movable parts. The compound flows into and fills the mould cavity and begins to cure simultaneously after the mould is closed and heat and pressure are applied; meanwhile forcing out the excess resin (the flash) (**Figure 9.10**). Presses with clamping capacities from 5 to 4000 tons are available for both manual and semi-automatic operations.

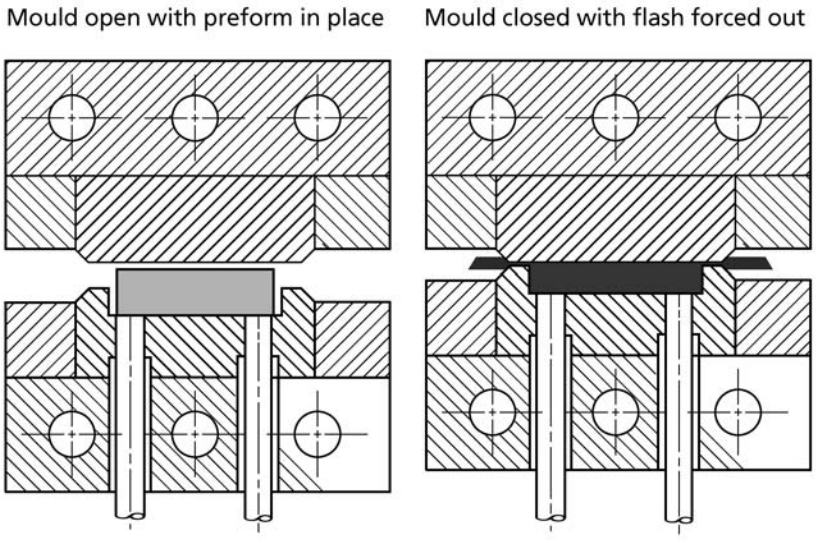

Figure 9.10 Compression moulding system with mould open (left), and closed (right)

The compression moulding technique is suitable for many forms of preform and premix mouldings, with a variety of fibre arrangements. Sheet moulding compounds (SMC) or prepregs, bulk moulding compounds (BMC) or dough moulding compounds (DMC) and MC are all processable by this method.

A typical composition for BMC and SMC includes base resins, catalysts, peroxides accelerators, fillers/chopped GF, thickeners and other additives. The base resins that are usually used are either polyester-based (orthophthalic or isophthalic), which are used with styrene, acrylic, vinyl toluene or di-allyl-phthalate (DAP) monomers, as crosslinkers, or styrene type monomers for general purpose products. Acrylic base resins are used for low shrinkage, while vinyl type monomers for high hot strengths (heat deflection temperatures). Catalysts are used for polyester type resins. Peroxides, such as benzoyl peroxide (BPO) and *t*-butyl perbenzoate are used as high temperature catalysts.

Compression moulded parts usually possess high rigidity and strength (tensile, compression and impact) along with good surface properties (gloss, smoothness, paintability), and in principle, the thickness of compression parts are not limited in size (in contrast to injection moulding).

Resin injection moulding is a cold moulding process applied at medium pressures (approximately 450 kPa), where mould surfaces are enriched with release agents and gel coat before GF reinforcement is placed on the bottom of the mould, allowing the plastic to extend beyond the sides of the mould. Then the upper mould is placed in its place and it is clamped to stop followed by injection of activated resin under pressure into the mould cavity (**Figure 9.11**). By using this technique, it is possible to obtain a fibre/matrix ratio of 65 wt%.

Injection moulding is a non-continuous process where a thermoplastic (or a reactive, thermoset) system is injected under high pressures into a closed three-dimensional mould through a reciprocating-screw, which plasticises the solid polymer forming melt. After that stage, the screw ceases to rotate and acts as a ram injecting the melt into the mould. The system can be used to process both thermoplastics and thermosets with certain variations in design, (i.e., for thermosets: barrels are shorter, heaters are only used at start-up followed by water coolers to remove the unnecessary heat), as well as in operation (use of lower compression ratios, higher temperatures in the moulds than the barrel, shorter cycle times and opening of the mould when it is still hot; all for thermosets). Heater bands existing on the barrel help to increase the temperature along the barrel. The mould is held at ambient temperatures (or at higher temperatures, in the case of a thermoset), where the product solidifies. Cooling and solidification (of the thermoplastic), or curing (of the thermoset) takes place while the material is kept under high pressure. With injection moulding, it is possible to have high production rates and high automation, although the cost is rather high due to the special moulds

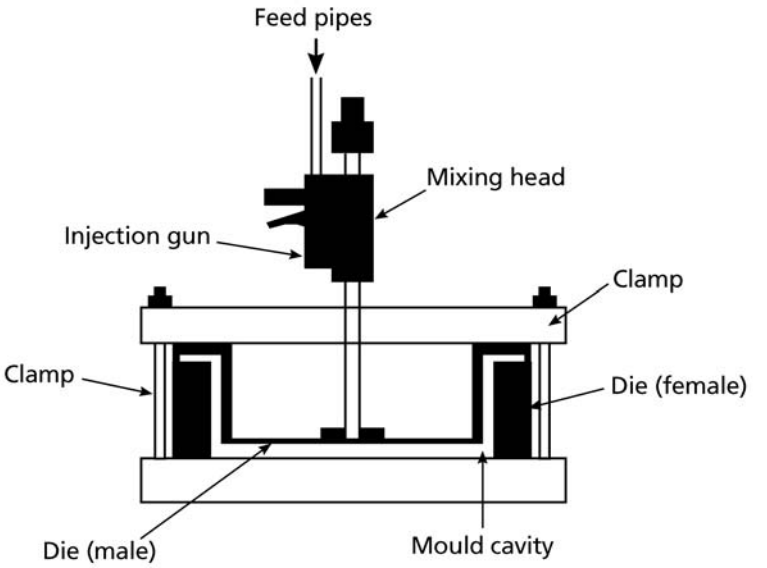

Figure 9.11 The resin injection set-up

involved. Since the quality of moulded articles are strongly dependent on the precision of repeatable cycle times (much more critical for thermosets), replacement of the human operator by robots for parts removal is usually very important. **Figure 9.12** presents the system schematically.

A few variations of the injection moulding processes are available, such as, injection moulding of pre-compounded resin with short GF and/or fillers and injection moulding under high pressure into a heated mould where GF fabric reinforcement is placed – also called structural reaction injection moulding, SRIM. The first of these is based on polyester (BMC/SMC) [7], as well as phenolics based on novolacs, while the second is based on PU (mixed polyol and isocyanate) injection which has the potential of low cost, low weight products where mineral fillers (RRIM) or glass mat reinforcements (SRIM) can be used. In RIM, two or more reactants are polymerised in the mould (for rapid reactions with short cycle times). In all RIM, there is substantial savings of energy in addition to the savings in the time element.

It is possible to perform injection moulding with very high speeds, (i.e., with common cycle times of 10-30 s). A recent process called foiled FibrePur technology (FFT), which is a plastic-foil finishing technique in RIM based on long-fibre reinforced PU which produces fully finished painted parts in a single-step process [8, 9].

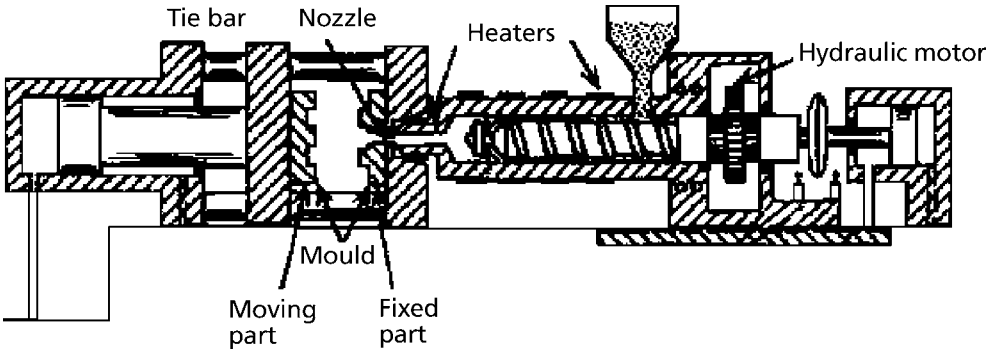

Figure 9.12 A typical injection moulding system

Anisotropy and fibre distribution in the case of short GF reinforced items cause the biggest disadvantage in injection moulding, as regards the final mechanical performance, however, the economy of process with short GF is much more promising than use of continuous fibres.

Pultrusion is a continuous, highly automated, closed mould composite manufacturing process that is widely used for both semi-structural and structural applications (such as window frames, cable coating, rods and bars, grids and meshes, beams and columns, panels and plates). The pultruded profiles sector is the most rapidly growing sector both in Europe and in US (with 10% and 15% annual growth rates, respectively). The possibility of pultruding with a wide range of different reinforcements, (i.e., GF, carbon and Kevlar fibres up to 60-80 wt%) and matrices (thermosets like polyester, epoxy, phenolic and a number of thermoplastics), as well as applicability of the pultrusion process beyond the traditional constant shape/section profiles, (i.e., pullshaping which offers a method for pultruding elongated non-linear composite elements, pullforming which is a method for producing products with variable cross sections by using a specially adapted temperature controllable pultrusion die, and pullwinding which produces high performance composite tubes by combining the techniques of conventional pultrusion and continuous filament winding) have opened ever increasing markets for this technique [10].

During pultrusion, the pultruder acts as a reactor. In the system fibres (either in the form of continuous tape, woven fabrics or mats) are first passed through a resin impregnation system (wet bath). This is followed by removal of excess resin. The pultrudate is then shaped in performing guides and go through the cure process in a heated die. The heated die has different heating zones and different geometrical shapes (like I, L, Tee and circular). Finally, the continuous composite pultrudate is cut off with a saw. In this process, the cure step is on-line. In pultrusion, continuous strand

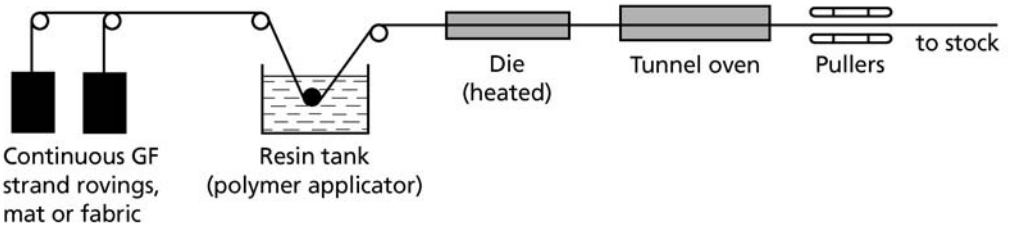

Figure 9.13 Schematic representation of the pultrusion process

GF rovings are used usually for unidirectional pultrusion and a continuous strand mat fabric (typically of glass/polyester) may be used to add off-axis fibres, as a reinforcement supplier. In the case of some thermoset resins with short pot lives, (i.e., phenolics, BMI and epoxy resins), the wet bath process is modified by directly injecting the resin into a fibre preform at the pultruder entrance (by using a pressurised pumping system). **Figure 9.13** shows a pultrusion process. Thermoset pultrusion is usually done by use of unsaturated polyester resin and GF spun from E-glass (E-GF) with 20% to 80% loadings of the latter, however, thermoset pultrusion has several disadvantages over thermoplastics, such as the limitations imposed on the process by cure rates and the fact that reinforcements are usually in the longitudinal direction with only a small percentage of fibres in the transverse direction. To avoid the latter disadvantage, the 'pull-winding' process was developed where fibres were wound in the transverse direction simultaneously with the pultrusion operation [10].

Pultrusion has been applied for production of a number of materials, including: pultruded FRP composite decks in elevated freeways, in The Netherlands [11], and production of pultruded reinforced fibre glass (FGR) windows and doors [12].

Extrusion: A range of different shapes can be processed by extrusion, such as, profiles for gaskets and sealing strips, window frames, rods, tubing, pipes, corrugated and normal sheeting, films, etc. The screw in the system works continuously on the Archimedean principle with approximately one revolution per second and there are considerably high pressures developed in the barrel (100 MPa). The characteristics of the screw can show differences from polymer to polymer: for polymers that melt abruptly (like Nylon 6,6) or slowly (branched PE) or for polymers that pass through a glass transition and plasticate slowly (PVC type), screws with different geometries are used. The extrusion system manufactures an endless product with a constant cross-section at the end, which is then cut, chopped, etc., to reduce it to the desired length. In the extrusion process, compound (solid feedstock) is fed into the feed throat from the hopper and is converted to a high viscosity paste by heat and pressure, and it is propelled

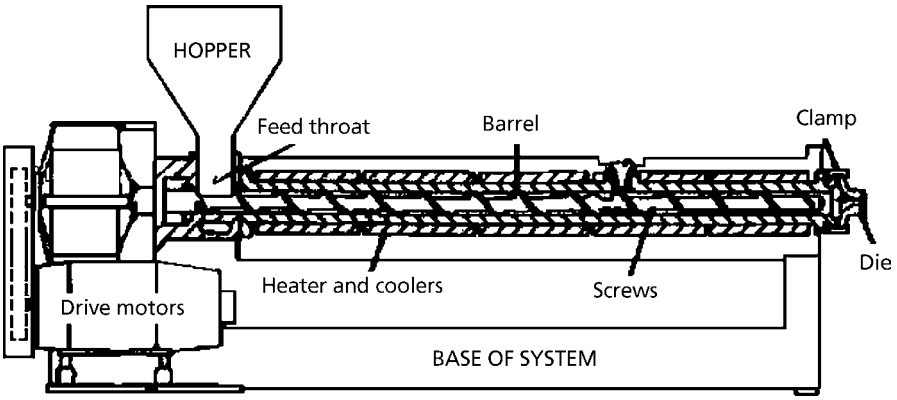

Figure 9.14 A typical extruder

continuously via a rotating screw (single or multiple), and forced at a constant rate through a die where it takes its final shape and solidifies. By co-extruding two compatible materials, a composite structure can be produced, (i.e., window frames can be made from unplasticised PVC (PVC-U) sections co-extruded with flexible plastised PVC (PVC-P) weather sealing strip or acrylic film with wood appearance). Short fibre composites can also be processed by extrusion and moulding. Other aspects of the extrusion process are presented briefly in Section 9.1.1. (**See Figure 9.4**)

9.2.1.3 Other Processing Techniques

The centrifugal casting technique can be used to get high production rates with automation and unusually large diameter dished bottom tanks can be made by this method. Centrifugal casting involves manually positioning mats or pre-impregnated components within a (hollow, cylindrical metal) mould located inside an oven. As the mould slowly revolves, catalysed resin is sprayed onto the mat, or roving may be chopped within and placed inside of the walls of the open-ended mould. By keeping the oven door closed and by heating the system, the mould is rotated at high speed causing centrifugal force to distribute and compact the resin and the reinforcement against the inside walls of the mould, prior to the resin cure. After the cure is complete, the mould is opened and the part is removed. This technique usually yields good surfaces – both inside and outside of the part, however, their mechanical properties are lower in general, than those produced by filament winding.

In the continuous laminating process, roving is chopped onto a supporting cellophane (or other) carrier sheet film with the resin, which is doctored and passed first through

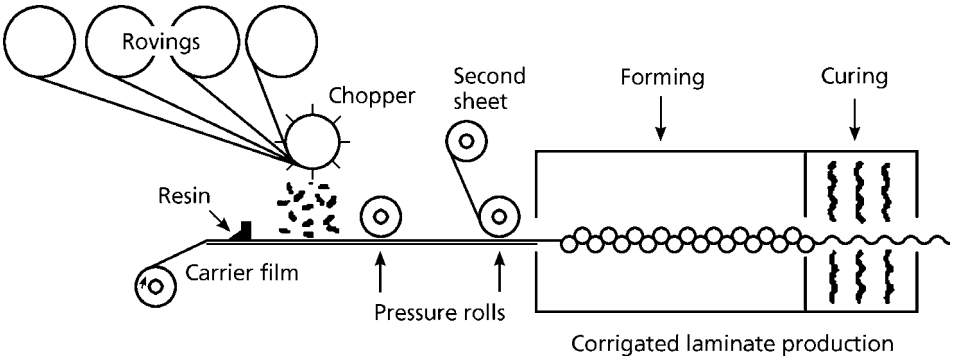

Figure 9.15 Diagram of a continuous laminating system

kneading devices (to eliminate entrapped air) and is covered continuously with a second sheet. It then passes through rollers to have controlled panel thickness and through a curing oven which may have shaping rollers for corrugations, if needed. When panels are stripped off the supporting sheets and cut to length, the laminate is ready. **Figure 9.15** shows a continuous laminating system.

9.2.2 Processing of Fibre Reinforced Thermoplastic Composites

Short fibre reinforced thermoplastic composites can be processed by most of the classical thermoplastic processing techniques, such as, extrusion and injection moulding. A detailed discussion is provided for these classical thermoplastic processing techniques in Section 9.1.

The most important technique to consider for reinforced thermoplastic composites is *injection moulding*. Since the melt viscosity is higher whenever fibres are included in the system, the injection pressures necessary are higher than their unreinforced thermoplastic counterparts. In addition, the product is much stiffer. Although the cycle times are less for reinforced thermoplastics, increased stiffnesses can certainly effect the ejection, hence the mould design needs to be modified considerably.

Another problem with thermoplastic composites processing is the fact that short fibres (approximately 0.2-0.4 mm long on average) are usually involved which are not long enough to impart their expected full strengths. Continuous tapes of fibres and mats (prepregs) are usually used to adjust this disadvantage.

9.3 On-Site Processing

On-site processing is very suitable for plastics materials and, in addition to the existing practices, there have also been studies to increase the proportion of on-site processing in construction, i.e., rolls of crosslinked polyethylene (XLPE) foam with a range of thickness and densities can simply be cut to the size and applied on-site.

In the earlier 'Nestehous', Concept House of Neste, Finland, the development of new on-site processing techniques were aimed at. Concrete casting moulds that stayed on the construction site were prepared from GFRP composites of polyester and they were used to prepare concrete rebars (prepared with concrete and PP fibres) used as the main load bearing material in the house.

Plastic composite bridges are very successful examples of on-site production: pultruded parts can be easily carried to the application site and processed (GFR resin – polyester thin-walled cellular modules were quickly assembled and bonded by epoxy-based adhesives on-site in a very short time in the Aberfeldy foot bridge).

Joining of plastic pipes is shown to be done more effectively, economically and in a much shorter time on-site by 'linear vibration welding', rather than the conventional hot plate welding or electrofusion welding techniques.

Sealants are materials used to seal joints in buildings or concrete slabs against the penetration of water or air; and they are one of the best examples of on-site processing. Seal joints can be expansion joints in concrete or masonry walls, they can be the joints used between glazing materials and its frames; or joints between precast concrete wall panels. Polysulfides offer good resistance to chemicals and fuels, silicones provide performance within a wide range of temperatures, and urethanes provide abrasion and chemical resistant seals; all of these being flexible. Sealants can be of two types, depending on their application: hot or ambient applied sealants.

Hot applied sealants provide excellent bonding, high resiliency with a positive seal; while ambient applied sealants are usually in the semi-cured state and can be one- or two-part.

One part-ambient sealants, (i.e., premixed sealants with polysulfide, silicone or urethane base and a catalyst) are applicable with a caulking gun on site, which cure chemically to give rise to sealants on-site with rubberlike properties. Pre-mixed two part sealants (the first part being the polymer base and the second is the catalyst) that are prepared and kept at low temperatures (approximately –20 °C) in boxes can also be applied directly on-site, after its thawing at room temperature. These pre-prepared types have the advantage of their availability in a range of hardnesses: from the softest types (used where there is maximum movement and minimum of strain) and medium grades (used if there is vibration movement) to hard types (for high abrasion resistance).

Epoxy pre-mixed putty sticks are well-known examples of one part sealants where epoxy in the premix is at a high cure consistency.

Two part ambient sealants (for example, chemically cured two part polysulfide or urethane resilient sealants) are applied on-site after mixing the two parts (the polymer-based part and the catalyst) within the pot life of the hardening of the system, which is usually one hour.

There are also preformed sealants to consider within the ambient type of sealants that can be applied on-site. They are pre-moulded and are fabricated from a range of materials (synthetic rubber, PVC) with different shapes (ribbons, tapes, beads, or extruded shapes), and are mainly used for glazing applications.

In situ foaming is an another typical on-site application used mainly for insulation purposes. Since rigid PU and polyisocyanurate foams provide the most energy efficient and versatile thermal insulations, they are preferable for use in roof and wall system applications, for both residential and commercial buildings.

In site foaming can either be 'pour-in place and foam' or 'spray on in-site' type.

Pour-in place and foam is a very attractive on-site method used for thermal insulation. This method, although not commonly used mainly due to its rather unfavourable economy, is very practical. The technique uses relatively simple equipment, and rests on the principle of pouring the specially formulated mixture to be foamed as a low viscosity liquid into the cavity to be filled (usually between the load bearing inner face of the wall and the weather resistant facade wall of brick-cement or masonry, for cavity wall construction or between metal boards to produce sandwich panels, etc.), where the mixture is left to foam and adhere the walls by sealing the cavity effectively.

For the pour-in place and foam technique, there is a group of characteristic rigid PU foam applications available, however, their largest consumption area is in the insulation of refrigerators and freezers, but not that much in the construction industry. Standard two-component formulations with special adaptations, or one-component systems that cure by reaction with the moisture existing in the atmosphere, are available. The method produces highly effective thermal and noise insulation as well as physical reinforcement, although the foams produced are less uniform than those produced in-plant.

Another cavity wall and foam technique is done by use of prefoamed EPS particles. The cavity between the two faces (walls) can be completely filled with the prefoamed expanded polystyrene (EPS) particles and then foamed by applying steam.

Spray-on *in situ* is an another attractive technique used mainly for thermal, (i.e., to produce spray-on insulating layer in roofing or coating on a wall) as well as for moisture

insulation; it also provides air barriers (to prevent condensation in construction systems at joints) and to produce vapour barriers. Sprayed PU foam provides weatherproof sealants, forms a seamless layer of insulation, and fills gaps, seams and covers irregular, hard-to-insulate shapes to make them more durable and easier to maintain. Spray PU foam has a closed-cell structure and with its high water and thermal insulation characteristics, they are very promising for residential and commercial building envelope insulation, as well as for air seal [13].

They are also rigid, and they generally are based on PU or PU-modified isocyanurates or polyureas.

The spray-on application technique is similar to paint spraying. Mechanical or pneumatic drive pumping units with mix heads are used, and to facilitate the foaming and curing (quickly, within 10 seconds) directly on the sprayed surface, without much draining, special formulations (containing high proportions of catalysts and foaming agents) are used to yield thicknesses of approximately 5 cm per application (for PU). PU spray-on products are structurally self-supporting, and can be attached to a wide range of substrates while requiring no additional adhesive.

Two liquid components (resin and catalyst) are combined, either within or immediately outside of a spray gun nozzle and are deposited in place by spraying. The chemical reaction created by the mixing at the nozzle causes the material to expand while it is sprayed 'onto' a wall (or 'into' a wall cavity). The foam expands up to 140 times its original liquid volume within seconds. Multiple layers can be applied by using multiple passes to reach the desired thickness. Spray PU foam (SPF) is most commonly used which typically rises and sets in between 5-15 seconds and it is dry to the touch in less than a minute. The scheduled phase-out of and hydrochlorofluorocarbons (HCFC) (in accordance with the Montreal Protocol, both of which were the blowing agents used for PU and they have been shown to deplete stratospheric ozone layer), caused the sharp decline in the strong, industrial position of PU to, although SPF with the highest R values (resistance to heat flow; 6-7 per inch) are still unbeatable in residential insulation. There are certain SPF techniques that use non-ozone depleting chemicals, such as water. A more detailed information on the subject is given in Chapter 6 (Sections 6.1.1.1, 6.1.1.2 and 6.1.2).

Spray-on *in situ* technique is a very effective one for insulation and sealing in construction applications, which requires rather simple but special equipment to meter, mix and spray [7]. However, mainly due to the wasted overspray, this technique is also not very economical: in addition to the fact that SPF applied usually needs a protective elastomeric coating to prevent and protect its surfaces from degradation caused by UV exposure [14].

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10 Lignocellulosic Fibre – Plastic Composites in Construction

Elsayed M. Abdel-Bary

10.1 Introduction

The application of lignocellulosic fibres in reinforcing plastics has been known for a long time. As early as 1908 the first composite materials were applied for the production of large quantities of sheets, tubes and pipes for electronic purposes (paper or cotton to reinforce sheets, made of phenol or melamine formaldehyde resins). In 1896, aeroplane seats and fuel tanks were made of natural fibres with a small amount of polymeric binder [1].

Because of low prices and the steadily rising performance of technical and standard plastics, the application of natural fibres for obtaining lignocellulosic fibre – plastic composites is widely used. More recently, the critical discussion about the preservation of natural resources and recycling has led to a renewed interest concerning natural materials with the focus on renewable raw materials [2].

Wood fibre as a lignocellulosic fibre possesses a number of potential advantages as a suitable candidate for fibre reinforced polymer composites. Among these advantages, those of major importance include low price, low density, low abrasiveness, and the absence of potential health hazards during processing. Besides, natural fibre reinforced plastics using biodegradable polymers, as matrixes, are the most environmental friendly materials, as they can be composted at the end of their life. There is currently a great deal of interest in updating the technology to incorporate cellulosics in plastic composites.

The field of natural fibre reinforced thermoplastic composite materials is now rapidly growing both in terms of industrial applications and fundamental research.

The use of lignocellulosics as fillers and reinforcements in thermoplastics has been gaining acceptance in commodity plastics applications in the past few years. It is interesting to note that the use of the lignocellulosics in commodity thermoplastics to reduce cost and/or to improve mechanical performance is not new, and there are plenty of published papers, including patents dating back to the 1960s and 1970s. The reappearance of interest in the 1990s is probably due to increasing plastic costs and the environmental aspects of using renewable materials.

Agro-based lignocellulosics suitable for composites come from two main sources. The first is agricultural residues and the second is those lignocellulosics grown specifically for their fibre. The first source includes rice husks or cereal straws, which are by-products of food or feed crops and can be used for everyday purposes such as animal bedding or fuel or alternatively are simply left on the field or burnt to reduce mass. Two examples of the second source are jute and kenaf. These plants also have residues, which are often used for bedding or fuel as well.

Technically speaking, almost any agricultural fibre can be used to manufacture composite panels. However, it becomes more difficult to use certain kinds of fibres when restrictions in quality and economy are imposed. The literature shows that several kinds of fibres have existed in sufficient quantity, in the right place, at the right price and at the right time to merit at least occasional commercial use.

This chapter briefly addresses the issues of using some of these fibre sources in composites production. More attention is given to the type of binders, either thermoplastics or thermosets used as matrixes for some selected fibres. The problem of compatibility of these fibres as polar materials and nonpolar thermoplastics such as polyolefins is discussed. Grafting of fibres as well as thermoplastics and their chemical modifications is discussed without going too deep into the mechanisms or chemical equations. The applications of corresponding composites are given and the effect of weathering governing the limitation of the application in one field or another is discussed. Evaluation of the performance of composites using standard testing methods is given briefly as it is given in detail in other chapters.

10.2 Sources of Lignocellulosic Fibres

While others may exist, a choice was made to only discuss bagasse, cereal straw, coconut coir, corn stalks, cotton stalks, jute, kenaf and rice husks [3, 4].

10.2.1 Bagasse

Bagasse is the fibre residue remaining when sugarcane is pressed to extract the sugar. Some bagasse is burned to supply heat to the sugar refining operation, some is returned to the fields, and some is used in various board products. Bagasse is composed of fibre and pith. The fibre is thick walled and relatively long (1-4 mm). For use in composites, fibres are obtained mostly from the rind, but there are fibro-vascular bundles dispersed throughout the interior of the stalk as well [5].

Special care must be taken during bagasse storage to prevent fermentation resulting from residual sugar content. To reduce the sugar content and increase storage life, bagasse is usually depithed before storage. The pith is an excellent fuel source for the sugar refining operation. Generally, if the bagasse is depithed, dried, and densely baled it can be stored outside; handled in a careful manner, bagasse can also be stored wet. In the wet method large bales of bagasse are specially fabricated and stacked to insure adequate air flow. Heat from fermenting sugars effectively sterilises the bales. Bagasse can be stored for several years using this method [6]. Other storage options are available, including some that keep the bagasse wet beyond the fibre saturation point.

As previously mentioned, only bagasse fibre is utilised for the production of high-quality composite panels. The fibres after depithing are more accurately described as fibre bundles that can be used for making particleboard, or they can be refined to produce fibres for fibreboard.

10.2.2 Cereal Straw

After bagasse, cereal straw is probably the second most important agricultural fibre for composite panel production. Cereal straw includes straw from wheat, rye, barley, oats and rice. Straw is also an agricultural residue. Unlike bagasse, large quantities of cereal straw are generally not available at one location. Storage is usually accomplished by baling. Their high inherent silica content results in increased tool wear compared to other lignocellulosic composites. Conversely, the high silica content also tends to make them naturally fire-resistant. Manufacturing plants are found in several countries, which make thick (5-15 cm) straw panels faced with kraft paper.

The straw is heated to about 200 °C, at which point the spring back properties are virtually nil and then the panels are made. The straw is fed through a reciprocating arm extruder and made into a continuous low-density panel. Kraft paper is then glued to the faces and edges of the panels. These panels can then be cut for prefabrication into housing and other structures. The low density of these panels makes them fairly resilient, and test data show that houses built using these panels are especially earthquake resistant.

For particleboards, straw is reduced by hammer milling or knife milling. For the production of fibre-based products, straw can be pulped by using alkali treatments and refining.

10.2.3 Coconut Coir

Coconut coir is the long fibre (15-35 cm) from the husk of the mature coconut and the average husk weighs 400 grams [7]. Coir is a fibre source for many cottage industries

and it is readily woven into mats and made into ropes and other articles for both domestic use and export. Coir has been used to produce a variety of composite products including particleboards and fibreboards. When used as a reinforcing fibre in inorganic-bonded composites, coir is very resistant to alkalinity and variations in moisture, when compared to other lignocellulosics [8].

10.2.4 Corn Stalks

A three-layer board having a corncob core and wood veneer face was produced for a short time in Czechoslovakia after World War II [9]. Corn stalks, like many agricultural fibre sources, consist of a pithy core with an outer layer of long fibres. Corn stalks and cobs are either hammer milled into particles or reduced to fibres in a pressurised refiner.

10.2.5 Cotton Stalks

Cotton is cultivated primarily for textile fibres, and little use is made of the cotton plant stalk. Stalk harvest yields tend to be low and storage can be a problem. The cotton stalk is plagued with parasites, and stored stalks can serve as a breeding ground for the parasites to winter over for next year's crop. Attempted commercialisation of cotton stalk particleboard was unsuccessful for this reason.

10.2.6 Jute

Jute is an annual plant of the genus Corchorus. Jute has a pithy core, known as jute stick and the bast fibres grow lengthwise around this core. Jute bast fibre is separated from the pith in a process known retting. Retting is accomplished by placing cut jute stalks in ponds for several weeks. The fibre strands are manually stripped from the jute stick and hung on racks to dry. Very long fibre strands can be obtained this way. If treated with various oils or conditioners to increase flexibility, the retted jute fibre strands are suitable for manufacturing into textiles.

Most composites made using jute exploit the long fibre strand length. Commercially, both woven and non-woven jute textiles are resin- or epoxy-impregnated and moulded into fairly complex shapes. In addition, jute textiles are used as overlays over other composites. Jute stick is used for fuel, and in poor areas it is stacked on end, tied into bundles, and used as fences and walls.

10.2.7 Kenaf

Kenaf is a form of hibiscus, and is similar to jute or hemp in that it has a pithy stem surrounded by fibres. The fibres make up 20-25% of the dry weight of the plant [10]. Kenaf grows well in warm climates and does not have the narcotic effect found in the non-fibrous parts of the hemp plant. Mature kenaf plants can be 5 m high.

Historically, kenaf fibre was first used as cordage. Industry is now exploring the use of kenaf in papermaking and non-woven textiles. Like jute, most kenaf composite products exploit the long aspect ratio of kenaf fibres and fibre bundles. One way to do this is to form the kenaf into a non-woven textile mat that can be used for erosion control, seedling mulches or oil spill absorbents. After a resin is added to the kenaf mats, they can be pressed into flat panels or moulded into shapes.

Standard screening and air separation techniques can then be used to separate the two different materials. Commercially, kenaf bast fibre separated this way can be purchased 98% pith-free.

10.2.8 Rice Husks

Rice husks are an agricultural residue that is available in fairly large quantities in any one area. Rice husks are quite fibrous by nature and little energy input is required to prepare the husks for the board manufacturer. To make high-quality boards, the inner and outer husks are separated and broken at their 'spine.' This can be accomplished by hammer milling or refining. Rice husks have a high silica content, and present the same cutting tool problems.

10.2.9 Other Fibre Sources

Other important fibre sources include flax shaves, bamboo, papyrus, and reed stalks. There are two varieties of flax: one is for fibre and the other is for linseed oil production. Bamboo is an important source of raw material for fibreboards in tropical countries. Most varieties of bamboo are fast-growing and produce strong fibres; particleboards have also been made from bamboo.

Papyrus is used in making hardboard in East Africa. Insulation boards and plastic-bonded boards have also been prepared from reeds. Other miscellaneous fibres include: banana leaves, grasses, palm, sorghum while many fibres have been used successfully in the laboratory to produce boards, most of these materials have not been used commercially because of cost or other factors [4].

10.2.10 Chemical Composition

As mentioned before, agro-based lignocellulosics suitable for composites stem from two main sources. The first is agricultural residues, which have unknown mechanical properties and the second source is those lignocellulosics grown specifically for their fibre. Examples of the second source are cotton, jute, flax, sisal and many others.

With the exception of cotton, the components of natural fibres are cellulose, hemi-cellulose, lignin, pectin, waxes and water soluble substances, with cellulose, hemi-cellulose and lignin as the basic components with regard to the physical properties of the fibres. The concentration of cellulose achieved is 82.7% in cotton and 64.4% in jute. In contrast hemi-cellulose concentration is 5.7% in cotton and 16.7% in flax. Pectin levels are 5.7% in cotton and 0.2% in jute. In contrast lignin levels are 11.8% in jute and 2.0% in flax and do not exist in cotton. The water content is 10% for cotton, jute, flax and sisal [11].

10.3 Types of Polymers (Binders)

The term 'binder' is used to mean the matrix in which the fibres are embedded or treated. The binders, sometimes called adhesives or matrixes, in this chapter refer to polymeric materials having reasonable mechanical properties. The binder may be thermosetting or thermoplastic polymers.

10.3.1 Thermosets

Thermosets are based on crosslinked polymers. They harden permanently with the aid of catalysts and/or heat, and cannot be remelted without degrading their polymeric structure. The thermosetting family includes phenolics, epoxides, alkyds, polyurethanes, melamine, urea-formaldehyde and unsaturated polyesters.

10.3.1.1 Phenol Formaldehyde

Phenol formaldehyde (PF) is two to three times as expensive as urea-formaldehyde (UF), but the increased durability for exterior applications makes it a popular resin. PF resins are typically used in the manufacture of products requiring some degree of exterior exposure durability, for example, oriented strandboard (OSB), softwood and plywood. These resins require longer press times and higher press temperatures than do UF resins, which results in higher energy consumption and lower production line speeds. Products using PF resins (often referred to as phenolics) may have lowered dimensional stability

because of lower moisture contents in the finished products. The inherently dark colour of PF resins may render them unsuitable for decorative product applications such as panelling and furniture.

10.3.1.2 Urea-Formaldehyde (UF)

The most common resin for lignocellulosic composites is urea formaldehyde. About 90% of all lignocellulosic composite panel products are bonded with UF [12]. UF is inexpensive, reacts quickly when the composite is hot-pressed, and is easy to use. UF is water-resistant, but not waterproof. As such, its use is limited to interior applications unless special treatments or coatings are applied. UF resins are typically used in the manufacture of products where dimensional uniformity and surface smoothness are of primary concern, for example, particleboard and medium density fibreboard (MDF). Products manufactured with UF resins are designed for interior applications. They can be formulated to cure anywhere from room temperature to 150 °C; press times and temperatures can be moderated accordingly. UF resins (often referred to as urea resins) are more economical than PF resins and are the most widely used adhesive for composite wood products. The inherently light colour of UF resins make them quite suitable for the manufacture of decorative products.

10.3.1.3 Melamine-Formaldehyde (MF)

Melamine-formaldehyde (MF) resins are used primarily for decorative laminates, treating paper, and paper coating. They are typically more expensive than PF resins. MF resins may be blended with UF resins for certain applications (melamine urea).

10.3.1.4 Isocyanate

Isocyanate as diphenylmethane di-isocyanate (MDI) is commonly used in the manufacture of composite wood products. MDI is used primarily in the manufacture of OSB. Facilities that use MDI are required to take special precautionary protective measures due to its toxicity. These adhesives have been chosen based upon their suitability for the particular product under consideration. Factors that must be taken into account include the materials to be bonded together, moisture content at time of bonding, mechanical property and durability requirements of the resultant composite products, and of course, resin system costs.

A more durable adhesive is PF. A third common resin, MF, falls roughly midway between UF and PF in terms of both cost and performance.

Natural options exist that might someday replace or supplement the synthetic resins listed previously. Tannins, which are natural phenols, can be modified and reacted with formaldehyde to produce a satisfactory resin. Resins have also been developed by acidifying spent sulfite liquor, generated when wood is pulped for paper. Wet process fibreboards frequently use the lignin inherent in the lignocellulosic as the resin [13].

Except for two major uncertainties, expectations are that UF and PF systems will continue to be the dominant wood adhesives for lignocellulosic composites. The two uncertainties [4] are the possibility of much more stringent regulation of formaldehyde-containing products and the possibility of limitations or interruptions in the supply of petrochemicals. One result of these uncertainties is that considerable research has been carried out in developing new adhesive systems from renewable resources.

Although research has indicated that a number of new adhesive systems have promise, their commercial use is currently limited. One example is the use of isocyanate adhesives. The slow adoption of this material is due to the relatively high cost and to toxicity concerns. This material does have some definite advantages from a variety of agricultural residues. Low-density insulating or sound absorbing particleboards can be made from kenaf core or jute stick. Low, medium, high-density panels can be produced with cereal straw. Rice husks are commercially manufactured into medium and high density products in the Middle East.

All other things being equal, reducing lignocellulosic materials to particles requires less energy than reducing the same material into fibres. Particleboards are used as furniture cores, where they are often overlaid with other materials for decorative purposes. Thick particleboard can be used in flooring systems and as an underlay. Thin panels can be used as panelling. Most particleboard applications are interior, and so they are usually bonded with UF.

10.3.2 Thermoplastics

Thermoplastics, based on linear or branched polymers, become rigid when cooled and soften at varying elevated temperatures (depending on the polymer resin type and additives). Thermoplastics can repeatedly soften and harden in response to heating and cooling, which makes them especially suitable for recycling.

The term wood-plastic composites (WPC) covers an extremely wide range of composite materials using plastics ranging from polypropylene (PP) to polyvinyl chloride (PVC) and binders/fillers ranging from wood flour to flax. These new materials extend the current concept of ‘wood composites’ from the traditional compressed materials such as

particleboard and MDF into new areas and, more importantly, a new generation of high performance products.

The first generation of 'wood composites' was a combination of recycled woodflour or chips and binders. These were ideal for relatively undemanding applications. The new and rapidly developing generation of WPC 'wood composites' have good mechanical properties, high dimensional stability and can be used to produce complex shapes. They are tough, stable and can be extruded to high dimensional tolerances. The new WPC materials are high technology products for the most demanding applications.

The most common types of the new WPC are produced by mixing wood flour and plastics to produce a material that can be processed just like a plastic but has the best features of wood and plastics. The wood can be from sawdust and scrap wood products. This means that no additional wood resources are depleted in WPC, waste products that currently cost money for disposal are now a valuable resource – recycling can be both profitable and ethical. The plastic can be from recycled plastic bags and recycled battery case materials although in demanding applications, new plastics materials are used. Thus it is interesting to use materials recovered from short life cycle applications in long life cycle applications. The benefits of WPC combine the best features of wood and plastics.

The final shape of WPC can be produced through extrusion processing. This maximises resource efficiency and gives design flexibility for improved fastening, stiffening, reinforcement, finishing and joining. WPC need no further processing: they are weather, water and mould resistant for outdoor applications where untreated timber products are unsuitable.

In recent years, increasing interest has focused on thermoplastic composites reinforced with wood fibre or with other lignocellulosic and cellulosic-based materials [14-17]. Lignocellulosics are favoured as new generation reinforcing materials in sources. Secondly, the increasing concern about our environment promotes recyclable raw materials and products, emphasising the demand for lignocellulosic – thermoplastic composite.

Typical thermoplastics are polyethylene (PE), PP, PVC, polystyrene (PS), acrylics, polyesters and polyamides.

Thermoplastics represent more than 80% of all plastics manufactured. Of these, the four major commodity plastics: PE, PP, PS and PVC represent nearly 75% of all synthetic polymers produced annually, or about 75 million tons worldwide. Filled thermoplastics represent a huge and growing market for all types of manufactured products. It is estimated that each year 20 million tons of fillers are used in plastic materials. Currently, the most important fillers are calcium carbonate, talc, silica, mica, clay, aluminium trihydrate, glass fibres, starch and cellulosic powders.

The lower thermal stability of natural fibres (up to 230 °C), limits the number of thermoplastics to be considered as matrix material for natural fibre thermoplastic composites. Only thermoplastics whose processing temperature does not exceed 230 °C are useable for natural fibre reinforced composites. These are, most of all, polyolefines, like PE and PP. Technical thermoplastics, like polyamides, polyesters and polycarbonates require processing temperatures >250 °C and are therefore not useable for such composite processing without fibre degradation.

Examples of the use of PE, PP and PVC in fibre-plastic composites are given in the next section.

10.3.2.1 Polyethylene (PE)

Use of thermoplastics reinforced with special wood fillers is rapidly growing due to their advantages. Lightweight, reasonable strength and stiffness are some of these advantages. The processing is flexible, economical and ecological. Since early times, wood has been a preferred, aesthetically pleasing, building and engineering material.

Meanwhile, if the attention is drawn to the replacement of wood products by WPC, the aesthetic features of the products are as important as strength issues for many applications. The addition of large quantities of wood-based fillers can supplement woody texture to the polymeric composites and this favourable feature can provide ample opportunities of applying these composites to much wider areas such as decorative panels. If wood-grain patterns on the surface of the products are needed, a coating or lamination process can be used. Furthermore, the present limits of the wood-plastic composites in the practical applications can greatly be overcome by the successful development of economic processes to generate wood-grain patterns on the surface of the extruded products.

Wood particles, such as chips, flakes, fibres, and wood pulps are used as reinforcement agents. Thus, previously wasted wood materials are converted into useful products, and this trend will probably accelerate in the future. The main problems of processing wood reinforced compounds are the variations in the quality of raw material, the compatibility limitations because of hydrophilic wood fillers and hydrophobic matrices, limited thermal stability during processing, and shape deviation of the component caused by the swelling of wood. The decomposition temperature of cellulose (about 220 °C) places an upper limit on the processing temperature for wood plastic composites. Fortunately the four major commodity polymers may be processed below this limit. The principal advantage of wood plastic composites is that they can be melt-processed. In this case the melt obtained is an intimate mixture of fibres dispersed into a plastic matrix as a result of blending at a temperature above the melt temperature of the plastic. The resulting mixture

of compounds can subsequently be fabricated into articles by common plastic melt-processing techniques, such as extrusion or injection moulding [18].

Waste Wood – Waste Thermoplastics Composites

The use of waste wood and post-consumer thermoplastics will help to solve the severe environmental and recycling problems. The increasing concern about our environment promotes recycling of thermoplastics for lignocellulosic-thermoplastic composites

However some problems are experienced if waste wood and waste thermoplastics are used. This is due to the fact that characteristic properties of these raw materials depend on the kind of treatment of the waste, on their origin, and on their age.

Also, high density PE, for example, is limited in use for structural applications by its low stiffness and high creep properties. By reinforcing the polymer with a stiff and strong filler this limitation could be overcome for some applications, thus increasing the marketability of the recycled polymer [19, 20].

The properties of polymer-wood materials based on virgin and recycled low density polyethylene (LDPE), PS, and their blends (LDPE-PS) were studied [21] and it was found that reactive groups in recycled polymers bring about chemical and specific interactions at the polymer-wood and polymer-polymer interface, thus improving the mechanical properties of these materials.

A promising new trend is the development of PWC based on ground wood and thermoplastics [22, 23]. Thus, the effects of woodflour on PE have been studied [24]

These materials differ from mineral-filled composites [23]. PWC based on recycled thermoplastics and their blends are of special interest because the desired compositions with the required service performance could be developed.

IR spectroscopic studies of virgin and recycled polymers show that virgin thermoplastics undergo chemical changes under the action of external factors (such as UV radiation, oxygen, or water), so that reactive groups form in them. For example, it is established that recycled PE contain unsaturated bonds of the R-CH=CH_2, vinyl type, ketones, ether groups of the =C-O-C type, and ester groups [23].

At the same time, the IR spectrum of recycled PS almost coincides with that of the virgin polymer because commercial PS is stable, and it is not subject to prolonged exposure to operating factors involving photochemical and thermo-oxidation processes. Because wood contains polar –OH, –OOH and –COOH groups, it is natural to assume, that PWC components are capable of specific (for example, hydrogen bonding) chemical interactions

between PWC components. The comparison of IR spectra of PWC based on PE and recycled PE filled with sawdust indicates that in addition to PE absorption bands, a spectrum characteristic of wood is observed, where the wood spectrum grows with the increasing filler loading. The bands at 1515 and 1585 cm^{-1} are due to C=C vibrations in benzene rings of wood lignin, whereas the band at 1730 cm^{-1} in the sawdust spectrum is due to absorption involving aldehyde groups [23].

The addition of wood fibre to high density PE (HDPE) increased the stiffness of the composites while the tensile strength decreased. To improve the adhesion between the filler and the polymer matrix, wood fibres were pretreated with a silane coupling agent/polyisocyanate before compounding with the polymer [25]. Tensile strength increased from 18.5 MPa (untreated fibre) to 35.2 MPa in isocyanate-treated fibre composites. Analysis of the filler cost/performance showed the advantage of wood fibre over glass fibre and mica [25].

Another critical parameter influencing the properties of these composites is the size of the fibres. Short and tiny fibres (average particle size 0.24-0.35 mm) are preferred. They provide a higher specific surface area and the fibres are distributed more homogeneously compared to composites with long fibres and so the compatibility of fibre and matrix is improved. In this case, swelling decreases and breaks during processing are reduced.

The application of wood fillers is limited mainly because of the changing in geometry due to moisture absorption and swelling. The hydroxyl groups (–OH) in the cellulose, the hemicellulose and the lignin build a large amount of hydrogen bonds between the macromolecules of the wood polymers. Submitting the wood to humidity causes these bonds to be broken. The hydroxyl groups then form new hydrogen bonds with water molecules, which induce the swelling. The swelling of wood exerts very large forces. The theoretical swelling pressure for wood is approximately 165 MPa. Such forces cause severe problems in wood composites, which are the major reason for their restricted use. Moisture absorption is increased with rising filler content in untreated wood – thermoplastic composites. An advantage of the presence of a large amount of –OH groups in wood fibres is that different chemical groups can be connected to the surface easily.

Blending different recycled polyolefins composed of 95% PE and 5% PP and reinforced with chemico-thermomechanicalpulp fibre (CTMP) have been studied [26]. The effects of fibre concentration, fibre surface treatment with acetic anhydride and PF, and sample storage time in water on tensile properties have been studied [26]. The authors found that strength and toughness of the recycled polyolefins were increased with addition of non-treated fibre. Addition of 30% fibre, by weight, in the polymer matrix, increased its Young's modulus up to 150%. Composites with 10% of treated fibre showed generally higher tensile properties than those containing 10% of non-treated fibre. For composites made with treated fibre, water sorption during storage time was lower and mechanical properties remained higher, compared with composites made from non-treated fibre.

The acetylation of CTMP fibre, and the treatment with the PF improves the tensile properties, especially the Young's modulus, of the composite containing 10% of fibre. Fibre treatment with acetic anhydride reduces the surface polarity of the fibre and improves the interfacial adhesion between the fibre and the polymer. The highest improvements were obtained with about 12% of acetic anhydride on fibre. Fibre could be deteriorated and lose its mechanical property if the acetylation degree is too high. Fibre was reinforced with the PF as a high modulus thermoset resin. Such reinforcement leads to the reinforcement of the composite. The highest improvements were obtained with around 12% of PF on the fibre. The dispersion of treated fibres becomes more difficult with a higher percentage of PP. Both treatments were less beneficial in injection moulding where the fibres experience higher rates of deformation than in compression moulding.

10.3.2.1 Polypropylene (PP)

Two major problems have been encountered in preparing wood fibre-filled PP composites. First, the affinity and adhesion between PP and wood is poor [27]. Second, the rate of thermal decomposition of lignocellulosics increases exponentially with increase in temperature and reaches a significant level in the processing range of PP (180-200 °C). This can result in the formation of tar-like products and acid products of pyrolysis, which can have various damaging effects not only on the processing machines but also on the ultimate properties of the composites. The properties of the composite of (PP) and CTMP reactively treated with bismaleimide-modified PP or premodified pulp showed that premodifications of PP, as well as pulp, with *m*-phenylene bismaleimide provided a positive response on the mechanical properties of the composites. The occurrence of chemical grafting reactions between PP and bismaleimide as well as between pulp and bismaleimide have been suggested, which can explain the difference in mechanical properties among different composites. *In situ* addition of sodium borate, boric acid, or phenolic resin during processing of the composite improves the flame resistance of PP.

The surface of wood fibres was modified by using silane coupling agents and/or coating with PP or maleated polypropylene [28-30]. Evidence shows that 180 °C is the best mixing temperature, while the use of vinyl-tris (2-methoxy ethoxy) silane with or without maleated polypropylene coating is the best surface treatment.

Cellulosic fibres used for reinforcement in nonpolar thermoplastics, such as PP, have to be modified because effective wetting of fibres and strong interfacial adhesion are required to obtain composites with optimised mechanical properties [31, 32]. Several methods for improvement in the adhesion between polymer and cellulosic fibres have been developed.

An attempt was made to chemically coat the wood fibres with PP through *in situ* PP polymerisation. In olefin polymerisation, silica is sometimes used as a catalyst support

because of its high surface area and good morphology. Silica reacts with the Ziegler-Natta catalyst through hydroxyl groups forming different active sites for olefin polymerisation. Wood fibres also present hydroxyl groups, which, similarly to silica, can react with a titanium catalyst, forming active centres so that a thin layer of the forming polymer on the wood fibres surface would be produced, as low activity should be expected for the system. A thin PP coating on wood fibres can facilitate the filler dispersion into the PP matrix and also improve adhesion between polymer and cellulosic fibres.

Besides poor dispersion characteristics in the thermoplastic melt and limited compatibility with the PP matrix, unsatisfactory final properties of wood fibres/PP composites are due to limited thermal stability during processing.

The effect of acetic, maleic or succinic anhydride modifications of wood fibre on the mechanical properties and dimensional stability of differently bonded fibre boards was studied [33]. The binders for the fibreboards used in that work were: powdered PF resin of the novolak type, PP and a combination of the two. Significant improvement in the mechanical properties was obtained as a result of the anhydride modifications. Thus, modification of wood fibres with maleic anhydride (MA) resulted in a reduction in the modulus of rupture of the PF and PF/PP-bonded boards, whereas acetylation and modification with succinic anhydride did not cause any significant changes in the modulus of rupture of the boards. The anhydride modifications improved the internal bond strength of the binder type used. Dimensional stability of the fibreboards was observed to increase significantly as result of the modifications [33].

10.3.2.2 Poly(vinylchloride) (PVC)

The problem of reinforcing PVC with fibres differs from that of polyolefins. This is because PVC needs another additive such as plasticiser, which should be added. The improvement in dispersion and adhesion between the wood particles and the polymer matrix showed that the mechanical strengths can be greatly enhanced, while the rheology or processing of thermoplastics/wood flour composites is seldom studied [34, 35]. Recently, the effect of low levels of plasticiser on the rheology and mechanical properties of PVC/newsprint fibre composites has been reported [36].

The addition of plasticiser would significantly reduce the viscosity of the composites. Thus, the shear viscosity and shear thinning behaviour of the composites can be tailored by varying the contents of wood flour and plasticiser [37]. The incomplete plasticisation of the high viscosity component might take place due to the premature plasticisation of the low viscosity component.

The authors found that the depression of glass transition temperature (T_g) due to the addition of plasticiser is substantially reduced by the loading of wood flour. In addition, various wood-plastic composites were compounded into different colours, and several pairs of the compounds with different rheological properties were extruded in single and twin-screw extruders to see whether any wood-patterns are developed. When the differences in the shear viscosity and the T_g of the two compounds were too large, the incomplete plasticisation of the higher viscosity component was observed due to the lower viscosity component. It was found also that distinct wood-patterns were only developed both inside and on the surface of the extruded products for the pairs of the composites with optimal differences in both viscosity and plasticiser content.

The effects of wood flour, acrylic impact modifier, and plasticiser on the rheology of PVC based wood-plastic composites have been presented. The authors tried to determine an optimal pair of wood-plastic composites that would exhibit substantially different rheological characteristics at high shear so that patterns similar to the grain of wood can be developed inside and on the surface of the product if two composites with different colours are extruded at once.

The shear thinning, and the shear viscosity were increased as the wood flour content was increased and they decreased with increasing temperature. Also, plasticiser significantly reduces the viscosity of PVC, while the addition of impact modifier to PVC yielded little effect on the shear viscosity.

It was also found that when the wood flour content was high, the addition of a large amount of impact modifier increased the viscosity of the composites. The depression of the T_g due to the addition of plasticiser can substantially be reduced by the loading of wood flour.

10.4 Wood-Plastic Composites

The production of WPC typically uses a fine wood waste (sawdust in the 40 to 60 mesh range) mixed with various plastics. The powder is extruded to a dough-like consistency and the profile is then extruded through a single-step die with no additional calibration and only a simple water bath for cooling.

Currently, most WPC are made with PE, both recycled and virgin, for use in exterior building components. However, WPC made with wood-PP are typically used in automotive applications and consumer products, and these composites have recently been investigated for use in building profiles. Wood-PVC composites typically used in window manufacture are now being used in decking as well. Polystyrene and acrylonitrile-butadiene-styrene (ABS) are also being used.

The plastic is often selected based on its inherent properties, product need, availability, cost, and the manufacturer's familiarity with the material. Small amounts of thermoset resins such as PF or diphenyl methane diisocyanate, as mentioned before, are also sometimes used in composites with a high wood content [38].

The wood used in WPC is most often in particulate form, e.g., wood flour, or very short fibres, rather than longer individual wood fibres. Products typically contain approximately 50% wood, although some composites contain very little wood and others as much as 70%. The relatively high bulk density and free-flowing nature of wood flour compared with wood fibres or other longer natural fibres, as well as its low cost, familiarity, and availability, is attractive to WPC manufacturers and users. Common species used include pine, maple, and oak. Typical particle sizes are 10 to 80 mesh.

Processing temperatures are less than 150 °C, a temperature that allows high processing rates and low energy consumption. During production, the flow characteristics of crosslinked composite, through the extrusion system, permit the use of simple dies for even the most complex profiles.

10.4.1 Additives

Wood and plastic are not the only components in WPC. These composites also contain materials that are added in small amounts to the compound prior to extrusion, which affect processing and performance. Although formulations are highly proprietary, additives such as coupling agents, light stabilisers, pigments, lubricants, fungicides, and foaming agents are all used to some extent. Some additive suppliers are specifically targeting the WPC industry [39].

10.4.2 Properties

With up to 70% of the WPC being cellulose material, the materials behave like wood and can be turned, drilled, sanded, sawed, mitred, routed, tenoned and planed like wood using conventional woodworking tools. WPC products can also be used with fasteners such as nails, screws and staples and can hold fasteners up to two to four times better than wood. This permits further design freedom since smaller fasteners may be used to achieve equal hold. Special adhesives can be used to provide excellent adhesion on all types of joints. During installation, silicone or acrylic seals and wood fillers can be used successfully.

WPC products are extremely moisture-resistant (water absorption of 0.7% compared to 17.2% for Ponderosa pine) with less thickness swell (0.2% compared to 2.6%). Since

there is little or no water present, fungal attack and decay are not issues. The coefficient of thermal expansion of WPC is very similar to that of aluminium and the mechanical properties can actually improve over time at higher temperatures. Low temperature performance is good and extrusions perform better than wood in temperature extremes. This flame resistance can be improved by the addition of flame and smoke retardants at the mixing stage to improve performance.

10.4.3 Applications

WPC have a wide range of applications. They can replace, cost-effectively, wood products in applications such as furniture, door frames, decorative profiles, window frames, cable trunking, roofline products and cladding, in fact anywhere that plastic shapes are used. WPC are true hybrid materials and combine the best properties of both wood and plastics. They use low cost and plentiful raw materials. Wood waste and recycled plastics become assets instead of liabilities. They are competitively priced and are competitive with traditional materials such as timber, MDF and PVC. They are easily produced and easily fabricated using traditional wood processing techniques. Decking, cladding and window frames are already on the market and are now being developed to use the improved physical properties of WPC.

10.5 Compatibility

The strength of composite materials formed by incorporating randomly oriented wood fibres into a plastic matrix depends primarily on the strength of wood fibre and on how effectively the polymer matrix is able to transfer externally applied loads to the fibres. The interfacial zone between the wood fibre and the polymer matrix must satisfy several mechanical and chemical requirements to obtain a useful composite:

(1) adequate bonding (preferably between fibre and matrix),

(2) maximum surface area of contact between fibre and plastics, and

(3) no chemical attack of the matrix by the fibre that would be detrimental to the strength of the composite or to the interfacial bonding.

The problem of compatability between the filler and polymer matrix can be overcome by modifying the filler-matrix interface [40-42].

Wood fibre is a polar substance primarily due to the presence of hydroxyl (OH) group in its constituent polymers. This leads to poor compatibility between the two types of materials and it confers poor mechanical properties and dimensional stability.

The quality of the fibre-matrix interface is significant for the application of natural fibres as reinforcement fibres for plastics. Physical and chemical methods can be used to optimise this interface. These modification methods have a different efficiency for the adhesion between matrix and fibre. Accordingly, one has to modify the surface of the fibres or the chemical structure of the plastic or use coupling agents.

Based on the increase in the mechanical properties of the PP-bonded boards, it seems evident, however, that the fibres have not been subjected to any significant loss of strength and if so, compensation for the loss of strength by improved compatibility is taking place.

According to the literature, the use of catalysts is needed in order to modify not only lignin and hemicellulose but cellulose as well [43].

Some authors used no catalysts or solvents to carry out the succinic anhydride (SA) and maleic anhydride (MA) modifications, which supports the assumption of the limited effect of the modifications on the fibre strength. It is not excluded that the improved interaction between the wood fibres and PP is related to more similar surface energies and even to chemical bond formation between the components.

On the other hand, Boeglin and co-workers [44], have reported that despite the lack of chemical compatibility between polyolefins and wood (unmodified), adequate mechanical adhesion between the materials can occur, leading to good mechanical properties of the composites. Evidence of the mechanical interlocking of the components in particleboards bonded with recycled polyethylene has been obtained by means of scanning electron microscopy (SEM) micrographs [44]. The authors state that SEM showed wood cells filled with the plastic. Furthermore, particleboards bonded with recycled polyolefins have been proved to have mechanical properties comparable to those of commercial particleboards [45, 46].

10.5.1 Surface Modification of Natural Fibres

10.5.1.2 Chemical Methods

Strongly polarised cellulose fibres are inherently incompatible with hydrophobic polymers [47]. When two materials are incompatible, it is often possible to bring about compatibility by introducing a third material that has properties intermediate between those of the other two. There are several mechanisms [48] of coupling in materials where coupling agents are used to eliminate weak boundary layers, produce a tough, flexible layer, develop a highly crosslinked interphase, improve the wetting between polymer and substrate and/or forming covalent bonds with both materials.

The development of a definitive theory for the mechanism of bonding by coupling agents in composites is a complex problem. The main chemical bonding theory alone is not sufficient. So the consideration of other concepts appears to be necessary, which include the morphology of the interphase, the acid-base reactions at the interface, surface energy and the wetting phenomena.

10.5.1.3 Change of Surface Tension

The surface energy of fibres is closely related to the hydrophility of the fibre. Some investigations are concerned with methods to decrease hydrophility. The modification of wood-cellulose fibres with stearic acid [49] causes those fibres to become hydrophobic and improves their dispersion in PP. As can be observed in jute reinforced unsaturated polyester resin composites, treatment with polyvinylacetate increases the mechanical properties [50] and moisture repellence. Silane coupling agents may contribute hydrophilic properties to the interface, especially when amino-functional silanes, such as epoxies and urethane silane are used as primers for reactive polymers. The primer may supply much more amine functionality than can possibly react with the resin at the interphase. Those amines, which could not react, are hydrophilic and therefore responsible for the poor water resistance of the bonds. An effective way to use hydrophilic silanes is to blend them with hydrophobic silanes such as phenyltrimethoxysilane. Mixed siloxane primers also have an improved thermal stability, which is typical for aromatic silicones [48].

10.5.1.4 Impregnation of Fibres

A better combination of fibre and polymer is achieved by impregnation of the reinforcing fabrics with polymer matrixes compatible to the polymer. For this purpose polymer solutions [51] or dispersions of low viscosity are used. For a number of interesting polymers, the lack of solvents limits the use of the method of impregnation. When cellulose fibres are impregnated with a butyl benzyl phthalate plastified PVC dispersion, excellent partitions can be achieved in PS. This significantly lowers the viscosity of the compound and of the plasticator and results in co-solvent action for both PS and PVC.

10.5.1.5 Graft Copolymerisation

An effective method of chemical modification of natural fibres is graft copolymerisation. Graft copolymerisation is generally effected, through an initiation reaction involving attack by a macroradical on the monomer to be grafted. The generation of the macroradical is accomplished by different means such as:

(1) a decomposition of weak bond or liberation of unstable group present in side groups in the chemical structure of polymer,

(2) chain transfer reactions,

(3) redox reaction,

(4) photochemical initiation, or,

(5) gamma radiation induced copolymerisation [52].

Thus, grafting is initiated by free radicals generated on the cellulose molecule. Afterwards the radical sites of the cellulose are treated with a suitable solution (compatible with the polymer matrix), for example, vinyl monomer, acrylonitrile methyl methacrylate or styrene [53]. The resulting co-polymer possesses properties characteristic of both, fibrous cellulose and grafted polymer.

After this treatment the surface energy of the fibres is increased to a level much closer to the surface energy of the matrix. Thus, a better wettability and a higher interfacial adhesion are obtained. The PP chain permits segmental crystallisation and cohesive coupling between the modified fibre and the PP matrix. The graft copolymerisation method is effective, but complex.

The polar nature of wood-based fillers also simplifies the chemical modification of the filler surface. Grafting is one of the most widely studied methods of improving adhesion at the fibre-matrix interface. By attaching a suitable polymer segment to wood fibres having a solubility parameter similar to that of the polymer matrix, the compatability between the polymer and fibre can be improved. Kokta and co-workers reported an improvement in the mechanical properties of PS filled with styrene-grafted hard wood fibres [54].

10.5.1.6 Chemical Modifications

There was range of new chemical treatments introduced during the period of 1930 to 1960. Some of the monomers are of the condensation type and react with the OH groups in the wood, while other chemicals react with the OH groups to form crosslinks. Another group of compounds simply bulk the wood by replacing the moisture content of the cell wall. A brief summary of the various processes of wood modification are acetylation, reacion with ammonia vapour or liquid at 1.03 MPa, crosslinking: using 2% zinc chloride as catalyst in wood then exposure to paraformaldehyde and heating to 120 °C for 20 minutes, reaction with acrylonitrile (this reaction using NaOH catalyst at 80 °C is known as cyanoethylation), or with ethylene oxide.

Chemical compounds which contain reactive groups such as the methanol group (-CH_2OH) as in methanolamine compounds are able to form stable, covalent bonds with cellulose fibres. This treatment decreases the moisture pick-up and increases the wet strength of reinforced plastics. Isocyanates are also suitable to modify the chemical structure via its reaction with the OH groups of cellulose. The mechanical properties of composites reinforced with wood-fibre and PVC or PS can be improved by an isocyanate treatment of those cellulose fibres or the polymer matrix. The improvement of the properties of the composites can be explained by the reduction in the number of OH groups responsible for moisture uptake and consequently the increase in the hydrophobicity of the fibre's surface

In addition, the esterification of wood with all the anhydrides studied, except acetic anhydride, has been shown to improve mouldability of wood. The effect of the anhydrides on the mouldability properties decreases in the order: succinic > maleic > phthalic anhydride [55].

The degree of thermo-plasticity achieved by chemical modification depends on several factors including: the type of chemical, the degree of substitution, the method used and chemical composition of the fibre. From the standpoint of reinforcing materials, it is essential that modification only takes place on the matrix of the fibre leaving the cellulose backbone unattacked [56].

Polyolefins perform well as binder materials for fibreboards but a slight improvement in the mechanical properties of the boards as a result of acetylation can be achieved [57]. Furthermore, acetylation increases the surface free energy of wood fibres leading to improved wetting of the fibre surfaces with melting thermoplastics and thereby to improved interfacial shear strength between the materials [58]. The anhydrides studied are known to form ester and hydrogen bonds with –OH groups of wood components and therefore were used to improve the adhesion between the wood fibres and PE [59].

By reducing free –OH groups in wood, susceptibility of the wood material to water and thereby to swelling is reduced. Acetylation of fibres had been carried out on an industrial scale with controlled reaction times among other parameters, which assures thorough modification throughout the whole fibre batch. Contrary to this, it was unclear to what extent the covalent ester bonding between the fibres and the powdered anhydrides (SA, MA) takes place during the short board pressing and post-treatment at 170 °C. However, the reduction in thickness swelling of the boards due to SA and MA modifications was considerable and did not differ from that of the acetylated boards, which leads to the conclusion that the modification level in the wood fibre was sufficient to result in boards with good dimensional stability [60].

Thus, the mechanical tests of the fibreboards carried out by the same authors [60] showed that chemical modification of wood fibre by means of anhydrides was most beneficial for the fibre boards bonded with PP, i.e., significant improvement in the mechanical properties

and dimensional stability of the PP-bonded boards took place as a result of the modifications. The observations on the positive effects of the modifications on the compatibility between PP and wood were supported by increased adhesion values between the PP films and veneer surfaces due to different anhydride modifications. Additional information on the improved interaction between PP and wood due to the modifications was gained from SEM studies of the fibre and veneer composites. In general, the modifications studied had a positive effect, although not always statistically significant, on the mechanical properties of fibre boards regardless of the binder used (PF, PP or both). Exceptionally, modification of wood fibres with maleic anhydride caused reduction in the modulus of rupture of PF and PF/PP-bonded boards. Improved dimensional stability of the fibre boards due to the treatments was prominent in all the modification and binder types.

10.5.1.7 Coupling Agents

An important chemical modification method is the chemical coupling method, which improves the interfacial adhesion. The fibre surface is treated with a compound, that forms a bridge of chemical bonds between fibre and matrix. The increase in the mechanical properties of the fibreboards due to chemical modification is an indication of improved interaction and stress transfer between the components. Some authors have reported that softening and increased thermo-plasticity of wood fibre surface facilitates contact and dispersion of the fibre with thermoplastics [61, 62].

The use of coupling agents is said to improve the efficiency of cellulose fillers in the thermoplastic matrix [63, 64].

10.5.2 Grafting Modifications of Plastics

Considerable efforts have been made in producing new polymer materials with an improved performance/cost balance. This can be achieved by (co)polymerisation of new monomers or by modification or blending of existing polymers. From a research and development point of view, the latter routes are usually more efficient and less expensive [65, 66]. Free radical grafting of monomers is one of the most attractive ways for the chemical modification of polymers. It involves the reaction between a polymer and a vinyl-containing monomer, which is able to form grafts onto the polymer backbone in the presence of free radical generating chemicals, such as peroxides [65, 66]. Such reactions can be performed in solution, yielding a relatively homogeneous medium because the reactants are easily mixed and the polymer and monomer are usually soluble. However, carrying out these reactions in the melt, i.e., via reactive extrusion, has economic advantages, as the modification is very fast and the need for solvent recovery is avoided.

Free radical grafting of maleic anhydride (MA) onto polyolefins has gained wide industrial use. MA modified polyolefins are an essential part of many plastics formulations. They are used as chemical coupling agents, impact modifiers, and compatibilisers for blends and filler reinforced systems [65-67].

Despite the large number of studies on MA grafting and the commercial success of MA grafted polyolefins, the chemical mechanism involved in the functionalisation process is not fully understood. Several studies have shown that the reaction pathways depend on the polyolefin molecular structure. When a peroxide is used as initiator, crosslinking or chain scission may occur simultaneously with the grafting reaction. The dominant side reaction for PE is crosslinking [68-76] and for PP is chain scission [77, 78].

Avella and co-workers [79] and Martinez and co-workers [80] showed that tacticity is also an important parameter and they found that the grafting level for atatic polypropene (aPP) was significantly higher than that of isotatic polypropene (iPP). Recently, considerable progress has been made in elucidating the structure of MA grafted polyolefins. It was shown unambiguously that the MA graft structure consists of single saturated MA units [81]. Grafting occurs on secondary and/or tertiary carbons depending on the polyolefin composition. When long methylene sequences are present, grafting occurs mainly on the secondary carbons. Actually, MA units seem to be attached to the polyolefin chain in close proximity to each other [82].

Despite the progress that has been made, the effect of the polyolefin composition on MA grafting is still not fully understood, due to the lack of true insight into the reaction mechanism. Actually, most grafting studies have been carried out using different grafting recipes (type and amount of peroxide levels for PP).

10.6 Processing

10.6.1 Thermosets

Detailed scientific information on the composting of composite wood material is limited, as the majority of information is presented as case studies in industry-based journals. The absence of solid information has significant implications, as composite wood products often possess a range of physical attributes and chemical ingredients that may affect handling requirements and end-product application. Consequently, significant caution and awareness of feedstock variability is required prior to establishing an operation for the composting of composite wood products.

Composite wood products may be constructed using wood fibres, flakes, chips or shavings, veneers or paper. During the manufacturing process, these materials are often combined

with different glues, resins, water repellents and preservatives to produce sheet boards. Some examples of major composite wood products include [83]:

Fibreboard (constructed from fibres of wood)
Particleboard (constructed from wood flakes, shavings or splinters)
Chipboard (constructed from wood flakes, shavings, splinters or paper)
Plywood (constructed from one or more veneers)

Each of these composite wood product types can be manufactured in a variety ways, comprising different physical or chemical attributes that may affect composting procedures and end-product applications. Furthermore, the prior use of these wood products will determine the presence or absence of such components as fasteners, nails, screws, bolts, plastic coatings and paint. It is therefore critical for the production of quality compost to be aware of how a wood residual was manufactured, its prior use, and its condition at time of recycling, (e.g., presence of fasteners, paint, etc., and moisture content).

The manufacture of composite wood products requires the use of bonding thermosetting resins mentioned before. In addition, to protect these products from biological degradation, (e.g., fungal induced decay), preservatives (insecticides and/or fungicides) are combined with resins or applied separately to the composite material. Other property-modifying chemicals such as waxes and fire retardants [84] may also be used.

Chemical processes such as acetylation are in some cases used to increase the water repellency of fibres in composite wood products [85].

10.6.1.1 Panel-Type Composites

The most common additive to lignocellulosic composite panels other than resin is wax. Even small amounts 0.5-1%, act to retard the rate of liquid water pick up. This is important when the composite is exposed to wet environments for short periods of time. However, wax addition has little effect on long-term equilibrium moisture content. Flame retardants, biocides, and dimensional stabilisers are also added to panel products [4].

10.6.1.2 Particleboards

Particleboard is produced by hammer-milling the material into small particles, spray application of adhesive to the particles, and consolidating a loose mat of the particles into a panel product with heat and pressure. All particleboards are currently made using a dry process, where air is used to randomise and distribute the particles prior to pressing.

Reducing lignocellulosic materials to particles requires less energy than reducing the same material into fibres. Particleboards are generally not as strong as fibreboards, however, because the fibrous nature of lignocellulosics is not exploited as well.

Particle Preparation

There are two basic particle types: hammer-mill type particles and flake type particles. Hammer-milled particles are often roughly granular or cubic in shape, and thus have no significant length-to-width ratio. For non-woody materials, flake-type particles are the most common. Their sizes are usually in the range of 0.2-0.4 mm in thickness, 3.0-30 mm in width, and 10.0-60.0 mm in length. Particle geometry significantly influences the board properties: the length of flake-type particles is probably most important as it influences maximum strength [4].

The most common type of machines used to produce flake-type particles are the 'cylinder' type and the rotating disc type. The cylinder type has knives mounted either on the exterior of the cylinder similar to a planer or on the interior of a hollow cylinder. For the rotating disc type, the knives are mounted on the face of the disc at various angles. The knife angle and spacing influence the nature of the flake obtained.

Classification and Conveying of Particles

It is desirable to classify the particles before they are used in further operations. When the particles are very small the surface area increases and thus the amount of resin required to wet the surface increases. Oversized particles can adversely affect the quality of the final product because of internal flaws in the particles. While some classification is accomplished using air streams, screen classification methods are the most common. In screen classification, the particles are fed over a vibrating flat screen, or a series of screens. The screens may be wire cloth, plates with holes or slots, or plates set on edge.

The two basic methods of particle conveying are mechanical and air conveying. The choice of conveying method depends upon the size of particles. In air conveying, care should be taken that the material does not pass through many fans resulting in particle size reduction. In some types of flakes, damp conditions are maintained to reduce break-up during conveying.

Drying

The moisture content of particles is critical during hot pressing operations. Thus, it is essential to carefully select the proper dryers and control equipment. The moisture content of the material depends on whether resin is to be added dry or in the form of a solution or

emulsion. The moisture content of materials leaving the dryers is usually in the range of 4-8%. The main methods used in drying particles include rotary, disc, and suspension drying.

A rotary dryer consists of a large horizontal rotating drum that is heated either by steam or direct heat from 100-200 °C. The drum is set at a slight angle, and material is fed in on the high end and discharged at the low end. The rotary movement of the drum allows movement of the material from the input to the output end.

A disc drier consists of a large vertical drum. It is equipped with a vertical shaft mounted with several horizontal discs with flaps. The particles move from the upper disc to the lower disc as drying progresses. Air is circulated from the bottom to the top. Drying time is usually from 15-45 minutes while the temperature is about 100 °C. A suspension drier consists of a vertical tube where the particles are introduced. The particles are kept in suspension by ascending air, resulting in rapid drying. As drying progresses, the particles leave the tube and are carried away by the air stream to be deposited as dried material. The drying temperature varies from 90 °C to 180 °C. High flashpoint drying is similar to suspension drying. It consists of a looped length of ducting approximately 40 cm in diameter. The temperature applied is high, approximately 400 °C. It may be necessary to pass the dried particles through a cooling drum to reduce the fire hazard and to bring the particles to the proper temperature for resin addition.

Resins and Wax Addition

Frequently used resins for particleboards include UF, PF, and to a much lesser extent MF, as described before. The type and amount of resin used for particleboards depend on the type of product desired. Based on the weight of dry resin solids and oven dry weight of the particles, resin content is usually in the range of 4-15%, but is most likely 6-9% [4].

Resins are usually introduced in water solutions containing about 50-60% solids. Besides resin, paraffin wax emulsion is added to improve moisture resistance. The amount of wax ranges from 0.3-1% based on the oven-dry weight of the particles.

Mat-Forming

After the particles have been prepared, they must be laid into an even and consistent mat to be pressed into a panel. This can be accomplished in a batch mode or by continuous formation. The batch system uses a caul or tray on which a cover frame is placed. Mat formation is induced either by the backwards and forwards movement of the tray or the backwards and forwards movement of the hopper feeder. After formation, the mat is usually pre-pressed prior to hot pressing. Producing a panel this way gives better material utilisation and the smooth face presents a better surface for overlaying or veneering.

Conventional composites typically use a heat-curing adhesive to hold the lignocellulosic components together. Conventional composites fall into two main categories based on the physical configuration of the comminuted lignocellulosic: fibreboards and particleboards. Within these categories are low, medium, and high-density classifications. Within the fibreboard category, both wet and dry processes exist.

Within limits, the performance of a conventional type composite can be tailored to its end use by varying the physical configuration of the comminuted lignocellulosic and adjusting the density of the composites. Other ways include varying the resin type and amount, and incorporating additives to increase water resistance or to resist specific environmental factors. On an experimental basis, lignocellulosics have also been chemically modified to change performance.

For three layer boards, the two outer layers consist of particles differing in geometry from those of the core. The resin content of the outer layers is usually higher, about 8-15%, with the core having a resin content of about 4-8%.

In continuous mat forming systems, the particles are distributed in one or several layers on travelling cauls or on a moving belt. Mat thickness is controlled volumetrically. Like batch forming, the formed mats are usually pre-pressed, commonly with a single-opening platen press. Pre-pressing reduces the mat height and helps to consolidate the mat for pressing.

Hot-Pressing

After pre-pressing, the mats are hot-pressed into panels. The temperatures of the hot press are usually in the range of 100-140 °C. Urea-based resins are usually cured between 100 and 130 °C. Pressure depends on a number of factors, but is usually in the range of 14 to 35 kg/cm^2 for medium density boards. Upon entering the hot press, the mats usually have a moisture content of 10-15% but are reduced to about 5-12% during pressing.

Comparison between cold and hot pressing of bagasse unsaturated polyester used as binding matrix [86] showed that better swelling resistant efficiency and higher dimensional stability of the corresponding composites were obtained with hot pressing than with cold pressing. Also, improved mechanical properties were obtained by the hot pressing technique. Besides, hot pressing offers relatively low binding costs since cold pressing needs a higher amount of resin than that of hot pressing to obtain the same results.

Alternatively, some particleboards are made by the extrusion process. In this system, formation and pressing occur in one operation. The particles are forced into a long, heated die (made of two sets of platens) by means of reciprocating pistons.

The board is extruded between the platens. The particles are oriented in a plane perpendicular to the plane of the board, resulting in properties which differ from those obtained with flat-pressing.

Board Finishing

After pressing, the board is trimmed to bring the board to the desired length and widths, and to square the edges. Trim losses usually amount to 0.5-8%, depending on the size of the board, the process used and the control exercised. Trimmers usually consist of saws with tungsten carbide tips. After trimming, the boards are sanded or planed prior to packaging and shipping. The particleboards may also be veneered or overlaid with other materials to provide a better surface and improve strength properties. In such products, further finishing with lacquer or paint coatings may be done, or some fire-resistant chemicals may be applied.

10.6.1.3 Fibreboards

Several things differentiate fibreboards from particleboards; the most notable of these is the physical configuration of the comminuted material. Because lignocellulosics are fibrous by nature, fibreboards exploit their inherent strength to a higher degree than particleboards. To make fibres for composite production, bonds between the fibres in the plant must be broken. In its simplest form, this is accomplished by attrition milling. Attrition milling is an age-old concept whereby material is fed between two discs, one rotating, one stationary. As the material is forced through the pre-set gap between the discs, it is sheared, cut and abraded into fibres and fibre bundles. Grain has been ground this way for centuries.

Dry Process Fibreboards

Dry process fibreboards are made in a similar fashion to particleboards. Resin (UF, PF) and other additives may be applied to the fibres by spraying in short retention blenders, or introduced as the wet fibres from the refiner are fed into a blow line dryer. Alternatively, some fibreboard plants add the resin in the refiner. The adhesive coated fibres are then air-laid into a mat for subsequent pressing much the same as particleboard. Pressing procedures for dry process fibreboards differ somewhat from particleboards.

After the fibre mat is formed, it is typically prepressed in a band press. The densified mat is then trimmed by disc cutters and transferred to caul plates for the pressing operation. Dry-formed boards are pressed in multi-opening presses with temperatures of around

190-210 °C. Continuous-pressing, large, high pressure band presses are also gaining in popularity. Board density is a basic property and is an indicator of board quality. Moisture content greatly influences density, thus, the moisture content is constantly monitored by moisture sensors using infrared light.

10.6.2 Thermoplastics

The manufacture of thermoplastic composites is often a two-step process. The raw materials are first mixed together in a process called compounding, and the compounded material is then formed into a product. Compounding is the feeding and dispersing of fillers and additives in the molten polymer. Many options are available for compounding, using either batch or continuous mixers. The compounded material can be immediately pressed or shaped into an end product or formed into pellets for future processing. Some product manufacturing options for WPC force molten material through a die (sheet or profile extrusion), into a cold mould (injection moulding), between calenders (calendering), or between mould halves (thermoforming and compression moulding) [87]. Combining the compounding and product manufacturing steps is called in-line processing.

The majority of WPC are manufactured by profile extrusion, in which molten composite material is forced through a die to make a continuous profile of the desired shape. Extrusion lends itself to processing the high viscosity of the molten WPC blends and to shaping the long, continuous profiles common to building materials. These profiles can be a simple solid shape, or highly engineered and hollow. Outputs up to 3 m/min are currently possible [88].

Although extrusion is by far the most common processing method for WPC, the processors use a variety of extruder types and processing strategies [89]. Some processors run compounded pellets through single-screw extruders to form the final shape, others compound and extrude final shapes in one step using twin-screw extruders.

Some processors use two extruders in tandem, one for compounding and the other for profiling [89]. Moisture can be removed from the wood component before processing, during a separate compounding step (or in the first extruder in a tandem process), or by using the first part of an extruder as a dryer in some in-line processes.

Equipment has been developed for many aspects of WPC processing, including materials handling, drying and feeding systems, extruder design, die design, and downstream equipment, i.e., equipment needed after extrusion, such as cooling tanks, pullers, and cut-off saws. Equipment manufacturers have joined together to develop complete processing lines specifically for WPC. Some manufacturers are licensing new extrusion technologies that are very different from conventional extrusion processing [89, 90].

Compounders specialising in wood and other natural fibres mixed with thermoplastics have fuelled growth in several markets. These compounders supply preblended, free-flowing pellets that can be reheated and formed into products by a variety of processing methods. The pellets are a boon to manufacturers who do not typically do their own compounding or do not wish to compound in-line (for example, most single-screw profilers or injection moulding companies).

Other processing technologies such as injection moulding and compression moulding are also used to produce WPC, but the total weight is much less than that produced with extrusion [91]. These alternative processing methods have advantages when processing of a continuous piece is not desired or if a more complicated shape is needed. Composite formulation must be adjusted to meet processing requirements, e.g., the low viscosity needed for injection moulding can limit wood content.

10.7 Testing Methods

Standards authorities require that wood-based structural members used in housing be assigned six mechanical properties: bending strength and modulus of elasticity, tension and compression strength parallel to the long axis of the member, compression strength perpendicular to the long axis of the member, and shear strength. These properties are established from standardised static test methods. For specific applications and materials other properties may also be required and may require the establishment of new test methods.

The three most influential groups which affect the acceptance or rejection of any new building product, component or system are building standard authorities, building contractors and consumers. While these three groups share many of the same concerns, code authorities typically focus on structural performance, contractors on application and cost savings, and consumers on aesthetics and durability. These five traits need to be considered when determining the acceptability of building products from WPC for building applications.

To assure that new products meet or exceed existing requirements for use as building components, and to avoid confusion for the consumer, newly developed WPC products are likely to be evaluated against performance criteria for existing solid wood products. In some cases it will be necessary to modify existing standards, or develop new standards to evaluate these newly developed products.

Engineering standards organisations such as the American Society for Testing and Materials (ASTM), the American National Standards Institute (ANSI), and the

International Standards Organisation (ISO) develop test standards and performance criteria for comparing properties across a range of products intended for a specific application. Such standards are essential for the acceptance of product performance criteria by building code authorities and need development for WPC.

There are two basic categories of acceptance standards: performance standards and product specifications. Performance standards focus on the ability of a material, component or assembly to resist the loads or environmental effects of its intended application. Product specifications focus on aspects of material quality, which may affect strength, appearance and durability. In some instances it may be possible to use existing standards directly with newly developed products and materials; in other cases it may be necessary to modify existing standards or develop new standards to assure equitable evaluation. Consensus committees comprising producer, consumer, and user groups develop performance standards, which are used to evaluate the engineering performance of wood-based panels, such as hardboard, MDF and particleboard. This standard was used because no standard exists for the evaluation of woodfibre-plastic panel materials.

A variety of material property and engineering tests were performed, including bending modulus of rupture (MOR), bending modulus of elasticity (MOE), tension strength, shear strength, thermal expansion, moisture absorption, hardness, and fastener withdrawal.

Some of the common standards used are ASTM D1037-94 [92], ASTM D2718-90 [93], ASTM D2719-89 [94], ASTM D3043-87 [95], ASTM D3044-76 [96], ASTM D3500-90 [97] and ASTM D3501-76 [98].

10.8 Environmental Effects

When fibre-plastic composites are used outdoors in construction building or as furniture, they are exposed to UV radiation, moisture from rain, snow and humidity, freezing-thawing and fungal attacks. The literature contains little data on the environmental degradation of organic composites. Simonsen [99] found that composites of wood or other biofillers in thermoplastics are not impervious to the effects of outdoor exposure. Degradation was noted especially in stiffness. English and Falk [100] found that WPC absorb very little water and observed that the linear coefficients of thermal expansion decrease with increasing fibre concentration. Coomarasamy and Boyd [101] examined the effect of the freeze-thaw cycle on the mechanical properties of plastic lumber and found that at the end of the temperature cycling, none of the samples showed any signs of cracking or other forms of deterioration, but several samples showed a reduction in

strength. All the plastic materials showed sign of oxidation with weathering. Unfilled PP showed detectable crazing and yellowing, while unfilled PE is more resistant than PP. The agro-plastics exhibited noticeable fading.

The durability performance of natural fibre-thermoplastic composites intended for use in roofing applications has been evaluated [102]. An accelerated ageing device was used to evaluate the effect of UV light exposure on the fading of various composites as well as the effect of weathering on the degradation of engineering properties. The results indicate low variability in fading and mechanical properties.

10.9 Conclusions

The huge amount of scientific papers, reviews, books and technical reports dealing with lignocellulosic fibres and their possible use in reinforcing plastics reflects the importance of this subject both from the scientific basis, and the technical, economical and environmental points of view. The mechanical and physical properties of natural fibres vary considerably depending on their chemical and structural composition, which depend on the fibre type and its growth circumstances. Cellulose, the main component of all natural fibres, varies from fibre to fibre. Almost any agricultural fibre can be used to manufacture composition panels. However, it becomes more difficult to use certain kinds of fibres when restrictions in quality and economy are imposed. The literature has shown that several kinds of fibres have existed in sufficient quantity, in the right place, at the right price and at the right time to merit at least occasional commercial use. The use of thermoplastics is going to replace thermosetting binders to obtain wood plastic composites. A marked development has been observed and expected to go further. Many questions however are still open, especially with the problem of using thermoplastic – thermoplastic blends or thermoplastic – thermoset blends as binders for obtaining wood-plastic composites. This topic is growing very rapidly as thermosetting processing is faced by many environmental precautions.

The moisture sensitivity of natural fibres is remarkable and easily influenced by environmental effects. Generally speaking, rising moisture content lowers the mechanical properties. The mechanical properties of composites are influenced mainly by the adhesion between matrix and fibres. Chemical modifications of the fibres or the matrix or using coupling agents can change the adhesion properties and at least improves the compatibility. So, special processing, such as chemical and physical modification methods were developed and are still in progress. These modifications also improve moisture repellency, resistance to environmental effects, and the mechanical properties are improved accordingly. Various applications of natural fibres as reinforcement in plastics, have proved encouraging. The development of processings and modification methods is not finished. Further improvements can be expected, so that it might become possible to substitute technical fibres in composites quite generally.

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11 Rubber Concrete

Han Zhu

11.1 An Introduction to Rubber Concrete

'Rubber concrete' represents a generic name for a mixture of conventional Portland cement concrete with crumb rubber, which is a granular material produced by shredding and comminuting used automobile tyres. In the USA, 250 millions of used automobile tyres are generated each year and there are about 2 to 3 billion used tyres already existing in landfills. The question of how to improve the properties of concretes in addition to how to simultaneously find new ways to reuse those used tyres, has been the main driving force for exploring new ideas, and rubber concrete has evolved from one of them.

There are about 40 research papers available in the literature on this subject worldwide, most of which involve mainly analytical and laboratory work.

The early research on rubber concrete begun at late 1980s and early 1990s. One of the early studies was carried out by Eldin and Senouci [1] to explore the effect of rubber chips and crumb rubber on the compressive and tensile (flexural) strengths of concrete mixes, and the use of rubber concrete in light-duty concrete pavements was suggested [2, 3]. In the same year, Biel and Lee experimented with a special (magnesium oxychloride) cement to enhance the bonding between rubber particles and cement [4]. Later, rubber concretes are shown to achieve higher toughnesses [5, 6], and the models of composite mechanics were provided [7, 8]. The issue of freeze-thaw durability of rubber concrete was first investigated by Savas and co-workers [9]; and later a compressive strength reduction model of concrete mixes versus rubber content was proposed [8], and the mechanics of crumb rubber cement mortar were also determined [10].

Xiao [11] characterised the role of crumb rubber as a distribution of mini-control/expansion joints within concrete. Recently, Zhu [12] did an extensive analysis of the air content increase due to the presence of crumb rubber in concrete and developed a method to mitigate such an increase for the purpose of bringing back the loss in compressive strength for rubber concrete.

Since 1999, a wave of pioneering effort to build rubber concrete test sites has been made in the state of Arizona by a coalition of Arizona State University (ASU), Arizona Department of Transportation (ADOT), Arizona Department of Environmental Quality

(ADEQ), Salt River Project, local concrete and tyre recycling industries. In February 1999, the author designed (about 23.6 kg of mesh #14 crumb rubber per cubic meter of fresh concrete) and supervised the construction of a section of rubber concrete sidewalk on the campus of ASU (warm climate). This sidewalk has entered its fifth year in service and it appears in excellent condition.

In May 2001, under the management of George Way, the chief pavement design engineer with ADOT, an 11 m by 11 m rubber concrete parking lot in ADOT's Phoenix Division site (warm climate) was built with a design of 35.4 kg of crumb rubber per cubic metre. In April 2002, three rubber concrete mixes without air entrainment agent were placed on the campus of Northern Arizona University (NAU) in Flagstaff, Arizona (cold climate), the purpose was to determine the possibility of reducing/replacing air entrained concrete with rubber concrete.

In December 2002, Thornton Kelley with Hanson Aggregates Arizona Inc., poured three large rubber concrete thin slabs as a truck loading area (5 cm in thickness and 177 kg of crumb rubber per cubic metre) without any joints at its plant in Phoenix, Arizona (warm climate). Two of the three slabs have the surface area that exceeds 46 m^2. In May 2003, a rubber concrete tennis court was constructed (two huge jointless slabs of 12 m by 11 m with a thickness varying from 3.8 cm to 10 cm) in Phoenix, Arizona (warm climate) with a design of 177 kg per cubic metre! In the same month, with the help from two engineers with Rinker Materials in Arizona, P. Hursh, E. Dennis, D. Pelley with Salt River Project (SRP) in Arizona and the author worked on spraying rubber shot-crete (118 kg per cubic metre) to repair a few sections of waste water cannel in Phoenix, Arizona (warm climate).

In June 2003, a section of rubber concrete (29.5 kg per cubic metre) roadway at a major intersection in the city of Cottonwood, Arizona (cold climate), was constructed by ADOT. The thickness for controlled concrete design was 23 cm. But for the purpose of testing the performance of rubber concrete, the thickness was reduced to 13 cm. In December 2003, ADOT built a second major road (29.5 kg per cubic metre and a small volume of fibres) in Sunland Gin near Tucson, Arizona (warm climate). There are about one dozen rubber concrete structures that have been built here and there in Arizona, and they so far are performing well.

11.2 Experience Related to Rubber Concrete Construction

Building these test sites has provided very useful experience and the means to evaluate first-hand, mixing, hauling, handling, pumping, placing, finishing, and curing of crumb rubber concrete.

Rubber concrete placed in all the test sites previously mentioned was mixed by the process described next, excluding the rubber concrete tennis court project. Fresh concrete was first mixed without crumb rubber in a batch plant, and then hauled to the job site by a concrete truck. Crumb rubber was then added to the truck on the job site, and a remix was performed. To make the crumb rubber disperse uniformly in a concrete truck, a per-metre based empirical formula of the re-mixing time needed for a regular concrete truck (about 7.6 m^3 capacity) is proposed here that states:

Remixing time = 180 seconds for the first 5.89 kg per cubic metre
+ 60 seconds for every additional 17.7 kg of crumb rubber/37 m^3.

The time computed by the above formula may be an overstatement. What has been observed is that 5-6 minutes remixing time is adequate for most rubber concrete to have a uniform distribution of rubber particles in concrete. When rubber content reaches 177 kg per cubic metre and over, the remixing time may be increased to 8-10 minutes. Also, when adding crumb rubber into a loaded mixing truck, the truck needs to be set spinning at 2 rpm to 4 rpm. When in re-mixing mode, 16 rpm is required.

This on-site remixing method means that crumb rubber was added at least 30 minutes after water was added and setting was beginning. On the other hand, it is speculated that most rubber concrete specimens made in a laboratory environment as reported in various studies referred to previously would have rubber and other materials mixed almost at the same time. Though whether the two ways to make rubber concrete will make a difference remains unanswered, it was noticed in one case from the rubber shot-concrete project that, the compressive strength for the specimens made in the laboratory was much lower than that measured on samples made from the job site.

It appears that addition of crumb rubber helps prevent the phenomenon of separation. When fresh, controlled concrete looks 'watery' with coarse aggregates being wrapped by 'thin and fluid' cement paste. With the presence of crumb rubber, the fresh mix appears more viscous or 'sticky', and less 'watery' as compared to controlled concrete. This is particularly true when the rubber content is high, say above the level of 58.9 kg per cubic metre.

When pumped and discharged from a hose, a satisfactory workability and little separation was observed in the project of constructing a tennis court. But the pumping pressure was set to 0.55 MPa, which was higher than the typical work pressure of 0.35 MPa. The explanation given by Thornton Kelly with Hanson Aggregates Inc., in Arizona was that since the rubber content was high (221 kg per m^3) it was a much more 'airy' mix so higher pressure was needed to push it.

For a rubber content under 59 kg per cubic metre, the slump may be reduced but not necessarily the flowability (workability). It appears more power or force was needed to

shovel rubber concrete or at least psychologically, but all the placing jobs were done with ease most of the time. When the rubber content is higher than 59 kg per cubic metre, it does reduce slump and workability in a significant way. Because of this a water reducer is needed. Tested water reducer brands showed that a mid-range water reducer might not be as effective to rubber concrete as to controlled concrete, but at least one brand high-range water reducer has worked very well with rubber concrete. This issue will be discussed further later in this chapter.

Polishing remains a challenge, especially when the rubber content is high. In the tennis court project, the rubber content was 177 kg per cubic metre. It appears that the polishing did not produce the result to the level of what to be considered satisfactory. In a comparison of current polishing machines, it is suggested that a lighter one with a higher spin speed may work better for rubber concrete.

Curing remains more or less the same. It appears that there have not been any problems in curing in all the projects previously mentioned, and most curing compounds used in those projects appeared to work well. Also, it is speculated that, allowing for the fact that rubber concrete has a water affinity, it may require less watering in a water curing treatment.

In summary, it appears there is no major hurdle to mixing, hauling, handling, pumping, placing, finishing, and curing of crumb rubber concrete.

11.3 Characterisation of Rubber Concrete

The number one damage mechanism causing concrete to fail is cracking. The reason is that concrete is very rigid and full of small air voids or micro-cracks. When absorbing heat, concrete tends to expand and so do those air voids or micro-cracks within. When the temperature drops, concrete will experience contraction. So will those air voids and micro-cracks inside the concrete. High stress concentration will then be induced around air voids or micro-cracks under the alternation of hot and cold temperatures. Such thermal based and repeated expansion-contraction fatigue is the main driving force that causes micro-cracks to grow. Upon the growth of micro-cracks reaching a certain level, they start to inter-connect themselves, giving birth to macro-cracks. This type of failure mechanism for micro-macro crack development and propagation in a brittle material is well observed.

It has been well studied in fracture physics that one way to help resist or slow the cracking process as described previously in a brittle material like concrete is to add soft reinforcement into the material. The theory is that those soft particles can reduce stress concentration at the vicinity of air voids or micro-cracks so as to prevent, or more precisely,

to delay the formation of macro-cracks from the merging of air voids or micro-cracks. It is well known that at the tip or frontier of micro-cracks, a high stress concentration exists under external forces or thermal expansion-contraction fatigue. Cleavage will take place along the direction that is normal to the contour of a crack tip/frontier into the material matrix that surrounds a micro-crack. But, when the tip of a micro-crack encounters or impinges on a soft inclusion, the stress concentration at the tip will be greatly reduced, so that the cracking process will be delayed or slowed in concrete [13].

In comparison with metals, concrete is an inhomogeneous material with the inhomogenity being very random spatially, so the stress field inside concrete may not be quite uniform even in a small scale, and is difficult to quantify the unevenness magnitude of the stress field. Concrete rupture is a dynamic process and depends on stress locality. One way to control crack development in a concrete structure is to introduce joints in it. Rubber grains in concrete may be considered as a distribution of combined control-expansion mini joints within. The theory proposed here is that those rubber grains provide a cushion space to re-justify or alter both the magnitude and orientation of stress distribution, playing a role like conventional control or expansion joints, but in a much smaller scale.

On the other hand, crumb rubber may be characterised as a special kind of sand, being extremely coarse, easily deformable and light in weight. It functions as distributed mini control/expansion joints inside concrete to intercept micro-cracks before they merge to form macro-cracks. Also, in the case of thermal fatigue, rubber can be easily 'yielded' to provide extra space for depleting internal stress or pressure build-up. In an analysis by Xiao [11] she estimates the role of rubber on thermal stress. In this analysis, a series connected model is used (See **Figure 11.1**) with both ends being fixed. Two cases of thermal stress are computed, one is with rubber (L_1 is finite), and the other is an extreme case when rubber is zero (L_1 is zero). The relative stress ratios from the former to the latter is tabulated in **Table 11.1** with two rubber content levels: 5.9 kg and 23.6 kg per cubic metre per metre. It can be seen from **Table 11.1** that thermal stress has been greatly reduced by the presence of rubber.

It should be mentioned that this model may not be universally true for representing the thermal behaviour of rubber concrete. Other models such as parallel connection may also be appropriate. It may take a lengthy discussion to quantify the modelling applicability, but the point to be made here is that for rubber concrete, internal stress/pressure build-up, which could be developed in controlled concrete, may be mitigated because of the presence of rubber particles inside.

Presence of rubber also makes concrete more ductile or 'giving'. **Figure 11.2** shows the force-time response (displacement control) for two compressive strength tests in which

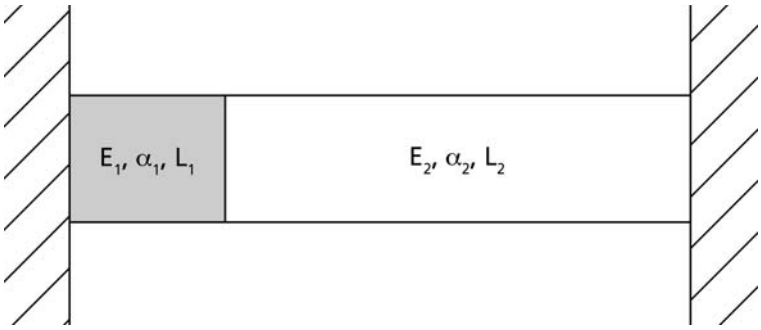

Figure 11.1 A series connected rubber-concrete bar model in which L_1 and L_2 represents the rubber and concrete portion, respectively, in a relative scale (L_1+L_2=1). E_1 (rubber) has a typical value range between 1 MPa to 14 MPa, and so does E_2 (concrete) having a typical value range between 24 GPa to 34 GPa. The coefficient of thermal expansion for rubber (α_1) and concrete (α_2) is set to be the same.

Table 11.1 Relative stress reduction due to rubber presence. L_1/L_2 = 0.006 or 0.036 which corresponds to rubber contents of 5.9 kg and 29.5 kg per cubic metre, respectively

	Relative stress reduction (L_1/L_2 = 0.006)	**Relative stress reduction (L_1/L_2 = 0.036)**
E_1/E_2 = 1/24000	0.007	0.001
E_1/E_2 = 14/24000	0.089	0.016
E_1/E_2 = 1/34000	0.005	0.001
E_1/E_2 = 14/34000	0.065	0.012

one specimen is made by controlled concrete and the other is made by the same mix design like the first one but with an additional 10 kg of crumb rubber per cubic metre. The area under the force - time curve for the rubber concrete specimen is about 20% higher that that for the controlled concrete. This means that the presence of rubber helps increase energy absorption capacity or toughness. This type of increased ductility and toughness for rubber concrete in comparison with controlled concrete has been widely observed including the study by Topcu [5]. Thong-On [10] drew the same conclusion after having conducted a number of similar tests on cement mortar specimens with and without rubber.

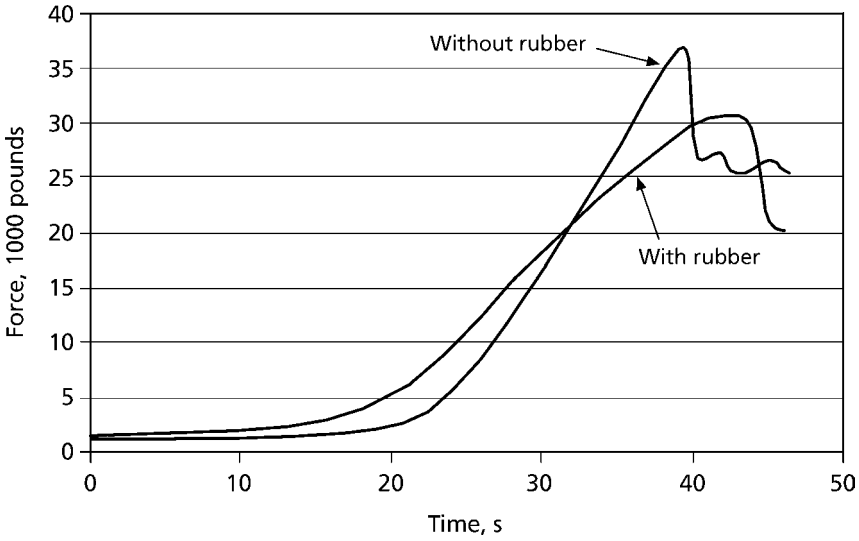

Figure 11.2 Force-time response for the compression of two concrete cylinders. The cylinder without rubber has a higher compressive strength but lower failure strain and energy absorption. The cylinder with rubber shows an opposite trend. Such a trend has been extensively observed in other similar tests [11].

Based on what is discussed in this section, and the physics and engineering properties of rubber and concrete, the characteristics of rubber concrete may be deduced as:

- Increased ductility and toughness.
- Increased crack and freeze-thaw resistance.
- Increased skid resistance, noise absorption and thermal insulation.
- Reduced Young's modulus, weight, drying shrinkage and thermal expansion.

So far the observation and laboratory test results generally support the characteristics listed above. For example, 0.02% dry shrinkage, 0.6% failure strain, 20-50% reduction in the coefficient of thermal expansion [11] have been achieved. The increase of energy absorption is 20% or higher in comparison with controlled concrete [5].

Rubber is organic and cement/concrete is inorganic. One question frequently asked is how the two can 'get along'? Is it true that rubber particles sit loosely inside concrete? The observations made so far indicate that rubber particles are embedded well in cement paste inside concrete, and they are not as easily removed from their bases as it is thought. It

should be pointed out that crumb rubber used in current studies is made by the ambient process, whether this is also true for crumb rubber made by the cryogenic process remains to be verified. Because of the work of placing and finishing, there are fewer rubber particles on the surface than in the interior. Rubber particles sitting on the surface of the sidewalk on the campus of ASU remain visible and intact after more than four years of 'wear and tear'. A more revealing case is when a diamond saw cuts through a rubber concrete cylinder. Most rubber particles on the surface area of cutting trail, though sticking out, still sit firmly on the surface area. The explanation is that rubber has a 'jaggy' surface that is filled with cement paste to form an interlock layer [11]. Also, concrete will undergo a shrinkage on drying that may make rubber particles as 'pre-stressed' reinforcement.

Is there any chemical reaction between rubber and concrete? Or will rubber participate in hydration in any capacity? It appears that it is inadequate to even try to answer this question. Yet, there have been a few cases observed in which the relationship of compressive strength versus time for rubber concrete does not follow the pattern of controlled concrete.

11.4 Air Content and Compressive Strength

As mentioned in Section 11.2, during the preparation for the tennis court project, a series of experimental test slabs (0.6 m x 1.2 m in size), with a thickness of either 5 cm or 7.5 cm) were poured in January 2003 in Phoenix, Arizona (warm climate) with rubber content varying between 29.5 kg to 177 kg of crumb rubber per cubic metre. The details of the pouring are as follows. Controlled concrete (Mix-1) of 3.8 m^3 arrived at the pour site after about 30 minutes of driving from the concrete plant and the first sampling and measurements were carried out. Afterwards, 114 kg of crumb rubber were added to the concrete truck to make a rubber concrete (Mix-2) with a rubber content of 29.8 kg per cubic metre and a re-mix for 6 minutes was performed. The second sampling and measurements were taken 20 minutes after the truck's arrival. Then more crumb rubber was added to the concrete truck to reach the level of 59.6 kg per cubic metre with sampling and measurements being done for the third time. The time gap between the truck's arrival and the third one was about 50 minutes. After that, the truck discharged more than 2.29 m^3 rubber concrete (Mix-3) into a pre-framed sidewalk and placing/finishing (rodding and trowelling) was done manually with relative ease. Then more crumb rubber was added to give a level of 89.3 kg per cubic metre, the rubber concrete (Mix-4) appeared very dry and extra water was added to the truck with re-mixing, which was 100 minutes after the truck's arrival. Mix-5 was made by adding more crumb rubber into the truck to give a level of 118 kg per cubic metre which was almost two hours after the truck's arrival. After that, another portion of water with rubber was added to give a level of 179 kg per cubic metre, which was called Mix-6, and made at about 130 minutes after the truck's arrival. Rubber concrete pads for Mix-4, Mix-5 and Mix-6 were also poured along with sampling and the measurements.

There was some speculation about whether those 179 kg per cubic metre rubber concrete pads (Mix-6) might disintegrate in any minute since its compressive strength was very low (see **Table 11.2**) as discovered later. But in the end, those pads still did what concrete was supposed to do, and have held up well since, though, with a very different and somewhat revealing characteristic in comparison with controlled concrete.

The measured data for Mix-1, Mix-2, Mix-3, Mix-4, Mix-5 and Mix-6 are given in **Table 11.2**, which shows that high air content was measured for rubber mixes. Since extra water was added to Mix-4, Mix-5 and Mix-6 and the air content was measured when those mixes were much 'older', the values for air content given in **Table 11.2** for those mixes may not have good repeatability. The pressure method, ASTM C231 [14], appears to be giving the low-end value, and the volumetric method, ASTM C173 [15], appears to be giving the high-end value. The air content can also be estimated by using measured unit weight, which yields somewhere in between the pressure and volumetric method. More details can be found in Zhu's recent paper [12].

The SRP project was to repair water cannel by spraying rubber shot-crete. The rubber content was 104.7 kg per cubic metre and the relevant information is given in **Table 11.3**, which again shows a high measured air content.

Table 11.2 Unit weight, slump, air content and strength history for the samples of tennis court preparation

Type	Unit Weight, $kg.m^{-3}$	Slump, cm	Air, % ASTM C173 [15]	Air, % ASTM C231 [14]	Strength 3rd day, MPa	Strength 7th day, MPa	Strength 28th day, MPa
Mix-1	2.37	12.7	2.9	1.7	20.1	25.3	30.0
Mix-2 (22.8 kg)	2.25	8.9	9.1	4.3	14.5	18.2	26.2
Mix-3 (45.6 kg)	2.16	5.7	13.0	6.1	11.1	14.1	16.9
Mix-4* (68.4 kg)	2.01	5.7	20.4	10.3	5.51	7.51	9.10
Mix-5* (91.2 kg)	2.02	2.54	20.8	8	5.17	5.78	8.48
Mix-6** (136.8 kg)	1.75	8.3	33.2	15	1.80	2.55	3.03

**extra water was added; **extra water was added the second time.*

Table 11.3 Air content information on SRP project			
Total weight	**Volume excluding air, m^3**	**Unit weight, g/cm^3**	**Air, ASTM C173 [15]**
1381 kg	0.63	1.81	17%

Besides the two cases given here, it has been consistently observed that rubber crumbs do bring air into concrete, though the quantification can be very difficult. This increase in air content may act as a major contribution to the loss of compressive strength.

Following the logic given previously that the increase in air content is to be blamed for loss of compressive strength, the question is to how to reduce the air content induced by the presence of crumb rubber. One method has been used to try and answer this question, in which 'additional' fine particles that were smaller than mesh #200, such as fly ash, dust collected from the asphalt plant and even gypsum powders were used. Here, 'additional' means to use more than what is normally specified in controlled concrete design.

In this experiment, three rubber concrete designs were studied with the same crumb rubber level: 148.79 kg per cubic metre. The details including both design specification and test results are given in **Table 11.4a and 11.4b** (Design-I), **Table 11.5a and 11.5b** (Design-II), **Table 11.6a and 11.6b** (Design-III). All the tests were performed by Dave Ruth and his staff at Speedie and Associates in Arizona, a licensed professional test

Table 11.4a Mix Specification for Design-I				
Materials	**Weight, kg**	**Specific gravity**	**Volume, m^3**	**Amount**
Cement (I/II)	428.50	3.15	136.03	
Fly ash	110.10	2.1	52.43	
Water	176.76	1	176.76	
Coarse	857.00	2.65	323.40	
Fine	196.40	2.65	74.11	
Crumb rubber	148.79	1.03	144.45	
Air (%)			95	9.5
Water reducer				2.4 kg/m^3
Gypsum				
Total	1917.55		1002.18	

Table 11.4b Test results for Design-I						
Slump	**Air content**	**Unit weight**	**1st day strength, MPa**	**3rd day strength, MPa**	**7th day strength, MPa**	**28th day strength, MPa**
20.3 cm	15%	1.86	6.48	10.7	11.9	14.4

Table 11.5a Mix Specification for Design-II				
Materials	**Weight, kg**	**Specific gravity**	**Volume, m^3**	**Amount**
Cement (I/II)	428.50	3.15	136.03	
Fly ash	110.10	2.1	52.43	
Water	176.76	1	176.76	
Coarse	797.49	2.65	300.94	
Fine	196.40	2.65	74.11	
Crumb rubber	148.79	1.03	144.45	
Air (%)			95	9.5
Water reducer				2.4 kg/m^3
Gypsum	42.85	2	21.43	
Total	1900.89		1001.15	

Table 11.5b Test results for Design-II						
Slump	**Air content**	**Unit weight**	**1st day strength, MPa**	**3rd day strength, MPa**	**7th day strength, MPa**	**28th day strength, MPa**
8.3 cm	9.5%	1.98	7.23	10.33	12.2	17.2

laboratory located in Phoenix, Arizona. Cement used in the tests is in compliance with ASTM C150 [16] type I/II, low alkali; coarse aggregate is in compliance with ASTM C33 [17]; size #7, 2.54 cm fine aggregate is in compliance with ASTM C33 size #1; fly ash is in compliance with ASTM C618 [18], type F; water reducer is in compliance with ASTM C494 [19]. Type A (high range); water is supplied from the city water source. Crumb rubber is the same grade as used for asphalt–rubber and is made by the

Table 11.6a Mix specification for Design-III						
Materials		**Weight, kg**	**Specific gravity**	**Volume, m^3**	**Weight, kg**	**Volume, m^3**
Cement (I/II)		428.50	3.15	136.03	327	2.8
Fly ash		238.06	2.1	113.36	181	2.3
Water		176.76	1	176.76	135	3.6
Coarse		687.39	2.65	259.39	524	5.3
Fine		196.40	2.65	74.11	150	1.5
Crumb rubber		148.79	1.03	144.45	113	3.0
Air (%)	10			10		2.1
Water reducer	2.4 kg/m^3					
Gypsum			2			
Total		1875.90		914.10	1430	20.6

Table 11.6b Test results for Design-III						
Slump	**Air content**	**Unit weight**	**1st day strength, MPa**	**3rd day strength, MPa**	**7th day strength, MPa**	**28th day strength, MPa**
25.4 cm	9.7%	1.88		13.8	17.2	21.4

ambient process. Gypsum is an industrial plaster with low dry compressive strength produced by United States Gypsum Company. On the test side, slump is in compliance with ASTM C134 [20], air content is in compliance with ASTM C231 [14], unit weight is in compliance with ASTM C138 [21], handling and strength testing is in compliance with ASTM C31 [22].

Design-I served as a starting point with the air content being at 15%, which was about right for this level of rubber content according to what has been observed previously.

Design-II featured added gypsum at the level of 42.85 kg per cubic metre (10% of the cement weight) as filler, other components remained the same as those in Design-I except

for a small reduction in coarse aggregate. The air content was dropped to about 9.5% and the strength increased.

Design-III was made, after examining the test results from Design-I and Design-II, with a high amount of fly ash and more than 50% of cement weight. In controlled concrete, fly ash usually takes about 15% to 20% of cement weight. The test results show an air content of 9.5%, 13.8 MPa for 3-day compressive strength, and 21.4 MPa for 28-day strength. The slump is 25.4 cm and the unit weight is below 1.9 kg/m^3 which qualifies as lightweight concrete. It appears based on the results given in **Table 11.6b** that this method can provide an improvement on strength recovery [12].

The second method is to premix crumb rubber with certain liquid polymers to 'squeeze out' air bubbles at the rubber/cement-paste interface. Polymer layers in-between rubber and cement paste may also help increase the bonding strength connecting rubber/cement paste. The issue with this method is that it may be costly [10]. It can be seen that reduction in air content will remain to be a major research issue in the days to come for rubber concrete.

11.5 Applicability

What is the possible application of rubber concrete? Before replying to this question, let's categorise three levels of rubber content in concrete:

Low level:	0 kg per cubic metre to 29.5 kg – 35.4 kg per cubic metre
Intermediate level:	29.5 kg – 35.4 kg per cubic metre to 88.3 kg – 147.2 kg per cubic metre
High level:	88.3 kg – 147 kg per cubic metre to 236 kg per cubic metre.

This categorisation is simplistic, yet it may provide a framework to quantify the applicability for rubber concrete.

At the low level of rubber, rubber concrete essentially functions like controlled concrete and it appears that one possible application is as a replacement for air entrained concrete. The results obtained from the test site in NAU indicate that, while it performs well in a cold climate, rubber concrete has the advantage of higher compressive strength than air entrained concrete. Also, while it has good ability to resist cracks, rubber concrete may be used as controlled concrete but with fewer or no expansion joints.

At a level of rubber between 88.3-147 kg per cubic metre, rubber concrete possesses all the characteristics given previously. Its Young's modulus is a fraction of that for controlled

concrete. It can achieve 3-day and 28-day compressive strength of 14 and 21 MPa, respectively, or more and a unit density of 1.9. Applications may include roadways, roofing, floors, shear and interior walls, etc.

At the level of 177 kg per cubic metre and more, rubber is in a very high concentration. For example, the level of 236 kg per cubic metre will have a volume of 0.18 cubic metre, and take about 25% of the total volume. Considering the air the rubber will bring in, rubber concrete at this level will be very light. In a few cases, the measured unit-weight values of rubber concrete at this level are as low as 1600 kg per cubic metre. Applications may include outdoor sports and recreational facilities like tennis courts, basketball courts, walkways, etc., with a design strength of 14 MPa or less.

Roads made with Portland concrete have been out of favour because of the noisy rideability, because of the high rigidity of concrete and the unevenness of expansion joints embedded in the roads as they age. Rubber concrete can also have low rigidity as close as that of asphalt concrete. It may also be acceptable to have narrowed expansion joints. The Arizona Department of Transportation has just built a major concrete road in October 2003 with a rubber content of 32.4 kg/m^3 and a small amount of glass fibres and polypropylene fibres. The soft cut method was used to make expansion joints so that the joint width was much narrowed in comparison to those ones made by the traditional method of forming. It has been reported in Spain that a concrete road with shredded rubber fibres (average length is 1.25 cm) was built three years ago, and it has performed well with heavy traffic flow [23]. It appears that there are a variety of ways to use rubber concrete in road applications aimed at various tangible benefits.

Dam and canal applications may present another market for rubber concrete for utilising its ability in resisting cracks. Rubber concrete may be used to provide 'more shock absorptive' joints in connecting rigid columns/beams in a building constructed in an earthquake active zone. The use of rubber concrete with steel reinforcement remains basically unexplored. It appears that more plausible applications for rubber concrete may emerge as the progress on rubber concrete is advancing.

11.6 Discussions and Conclusion

One question that has been asked is whether rubber will contribute anything other than to function likes air bubbles inside concrete? To answer this question, an analysis is given here in which the staring point is the mix design given in **Table 11.6a and Table 11.6b.** Since rubber takes 14.8% volume and the air content is 9.5%, the equivalent air content for combined air and rubber is 24.3%.

Taking an assumption that 8% air increase will yield a compressive strength reduction by 50%, and assuming a mix design that has 165 MPa 28-day compressive strength with 1% air content, as a deduction, the same mix design now may have 82.2 MPa at the air content being somehow raised to 9%, and 41 MPa at the air content being 17% and 20.5 MPa at the air content being 25%, respectively. Based on this deduction, this means that if all the air bubbles including rubber were to be squeezed out in the mix design given in **Table 11.6a and Table 11.6b**, the level of compressive strength at 165 MPa would be reached. Certainly, removing the rubber component out of the mix recipe given in **Table 11.6a** would not make it a 165 MPa concrete. This may suggest that rubber crumbs may do more than just be air bubbles inside concrete.

On another note, rubber concrete appears in a product called 'elastic concrete' with characteristics in between asphalt concrete and conventional Portland concrete. So far, the concrete design is governed by the concept of strength, and rubber concrete may be an alternative, or at least a thought of as the alternative, not only because of its strength but also because of its toughness.

Rubber concrete is in its infancy and much remains to be explored. Admittedly, the cases presented here are limited in number with many analytical analyses, deductions, and observations. It is hoped that more progress will be made that will shed more light on rubber concrete.

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12 Some Possible Health Issues Related to Polymeric Construction Materials and on Indoors Atmosphere

Güneri Akovali

12.1 Introduction

The environment of modern society is full of toxic chemicals. In the case of indoors, where there is a closed environment, the concentration of toxic chemicals can be even higher and thus more critical. Some researchers have suggested that even minute amounts of certain chemical compounds can act directly or may adversely change the way humans and wildlife develop and reproduce. These toxic chemicals may already be existing naturally indoors, such as radon, or they may come from materials of construction (flooring materials, wall-papers, wooden structures, various furniture, paints, etc.), or even from common household products (such as cleaning agents). This exposure usually is done unintentionally and in most cases without knowing it. However, hazards resulting from exposure to some of these possibly toxic chemicals that exist indoors and their effect on health may be a very serious issue. Effects of them on health are usually neglected and, in fact, they are one of the least known issues in our living sphere. However, as shown in the following examples, they should be considered more seriously because their effects can be important and even vital, and, they may be the reason for a number of health problems from the long-lasting allergy or asthma or even a lasting headache, to more serious issues, like cancer.

These possible sources will be discussed briefly next, by considering natural but with the emphasis on plastic construction materials. It should be noted, however, that inclusion of plastics in general should not automatically mean that its use will result in adverse health effects. Many plastics are being used in many critical areas, including food packaging and health sector, even as blood bags and dialysis equipment tubing; this shows that in most cases it is not the plastic itself but the additives and other foreign chemicals that are added for different purposes that can pose health hazards and should be carefully considered. This being the case, the same plastic material can be very safe or very hazardous; depending on the ingredients added to it.

To begin with, general aspects of poor indoor air quality (IAQ) and sick building syndrome (SBS) will be discussed, which will be followed by the other possible 'toxic' issues indoors.

12.1.1 Indoor Air Quality (IAQ) and Sick Building Syndrome (SBS)

IAQ and SBS are also known as Building Related Illnesses (BRI). We usually spend most of our time indoors where chemical concentrations can be significantly higher than outdoors, and hence air quality in homes and in offices is a matter of ever increasing concern. In addition, there are a number of different materials existing indoors, most of which are arising from furniture and construction. New consumer products increased the variety of pollutants in the indoors air. Volatile organic chemicals (VOC) emitted by building materials, furnishings, cleaning products, carpets and other materials found or used indoors as well as occupant activities can accumulate to detectable (and sometimes to harmful) concentrations; hence they should be considered seriously in most cases. In fact, the Environmental Protection Agency (EPA) has listed both IAQ and SBS as one of the top five environmental problems.

Adverse health effects that are associated with increased VOC concentrations can begin with eye and respiratory irritation (including asthma), irritability, inability to concentrate and sleepness, and can end up with various disorders in health and even with cancer. In a report [1], it is shown that 7-10% of the population suffers ill health, usually as a direct result of poor IAQ.

Indoor environments can also concentrate biological contaminants (such as bacteria, fungi, moulds, pollens, arachnids and insects) which can lead to various allergies and health problems. Since biological contamination is beyond the scope of this chapter, it will not be discussed at all and only chemical contamination indoors will be focused on briefly, although in over 40% of SBS cases there is bacterial or fungal contamination involved.

SBS is directly connected to IAQ and it is simply due to the 'poor indoor air quality'.

12.1.2 What is SBS?

SBS is a serious air quality problem in homes, as well as in work places. An area can be described as 'sick' mainly because people develop symptoms of illness such as headache, watery eyes, nausea, throat irritation, skin disorders and fatigue when spending considerable time indoors where there is a build up of air pollutants from household products, building materials, formaldehyde and/or respirable particles, and there is no precise definition of SBS. There are several important notes to consider:

(a) Signs of a sick house usually include a musty, stuffy smell and other odours,

(b) Moisture build up indoors plays a large part in SBS since high humidity increases the emissions of odours and chemicals such as formaldehyde, and it promotes the spread of mildew which can aggravate or cause allergies.

(c) Since everyone's tolerance level and metabolism are different, SBS can have an affect on only one of the occupants while the others in the same environment may not be affected.

(d) In the classic case of SBS, sufferers report relief of their symptoms once they cut off their exposure to the building.

An area of concern several years ago was new carpeting which sometimes released vapours, however, this is regulated by standards for emissions. There is also interest in some other synthetics, such as vinylics with phthalates, as a source of some SBS problems, which is still under investigation and will be discussed in following sections.

As regards the 'diagnosis' of a sick building, the rule of thumb is as follows: when at least 20% of building occupants 'complain of the same medical symptoms from an unknown cause for at least two weeks' the building can be suspected of being 'sick'.

SBS is rather a misnomer in as much as the syndrome can only be diagnosed by assessing the health of the building occupants, not by an examination of the building itself.

The oil crises during 1973-1974 and 1980-1981 agitated the development of super-tight, highly insulated houses in an effort to make homes more energy efficient. As building enclosures become tighter to reduce the exchange of air between the indoor and outdoor environments in building technology, the less effective is the dilution of pollutants in the indoors space. Although no solid correlation between tight houses and health problems exists, still some tightly built, well-insulated and vapour-sealed houses are known to develop signs of a sick house especially during winter months, in moderate and cold climates. The cure for this is proper ventilation, because cool air holds less moisture and replaces air that is moist and contains contaminants. In warm, humid climates SBS can occur during summer months when the outside air is very moist. Infiltration and ventilation, which bring humid outside air in, may increase mildew and other moisture related problems when air conditioning does not provide sufficient dehumidification. In most cases, the ideal relative humidity range should be between 37 and 55%.

Concentration and emission rate build up of pollutants indoors depend mainly on [2]:

(i) the characteristics and the nature of the material(s), i.e., volatility,

(ii) parameters such as temperature, relative humidity and surface air velocity, and,

(iii) for solid materials, the age of the material, i.e., formaldehyde, which is used in wall panelling and kitchen cabinets has a half-life of 3-5 years [5]. Outgassing decreases with time.

It is thought that some 800,000 to 1,200,000 buildings in the USA have been 'diagnosed' as sick. In 1987, the Polk County Courthouse, in Barstow, Florida, USA, constructed at a cost of $37 million, had to be demolished and built again with an additional cost of $26 million in order to 'cure' the building of its 'sickness' which had necessitated the relocation of over 600 occupants of the courthouse due to their claims of sick building symptoms. There are a number of Court Rulings known, mostly in USA, involving SBS cases. There are also cases of long-term disability claims and court orders for employers claiming total disability as a result of sick-building syndrome [3, 4]. Consequently, the SBS issue has become unsettled and scientists still continue their efforts to understand what it is about some buildings that makes some of the occupants sick.

According to a study accomplished by US Federal Environmental Protection Agency (EPA), 'indoor air is often a greater source of exposure to hazardous chemicals than is outdoor exposure'. The air quality inside most houses can be 5-10 times worse than that outdoors [5].

12.1.2.1 Some Solutions to Combat Existing SBS

An IAQ problem can be of natural origin or it can be due to various VOC emissions from different indoors sources, mostly associated with inadequate fresh air. Deterioration of IAQ eventually leads to SBS. Hence, availability of fresh air is very important in combating this problem. In principle, a house should have complete air change regularly. A typical old house is expected to have more frequent air changes due to possible leaks (natural stack effect). In any case, the need for air-change component can be decreased if more electric heat and heat pumps are used in place of gas furnaces and water heaters in the house. If heated by gas, an airtight house can have carbon dioxide levels two to six times higher than outdoors which can make one to feel sluggish and sleepy. Other common pollutants are from construction materials, household cleaners, gases from furniture and carpet, etc.

Heat recovery ventilator (HRV) is the most efficient method to bring in fresh outdoor air all year-round and which is much more efficient and controllable than just opening windows. HRV incorporate one of several designs of heat exchanger cores.

Heating and air-conditioning systems keep a building warm in winter and cool in summer, however, they do not help to improve the air quality in the house. A total heating-ventilation and air conditioning system (HVAC), which should include a furnace, an air filter, humidifier, make-up-air unit and air conditioner, is very effective in improving IAQ. If the HVAC system used is not total, it can cause the circulation of harmful, contaminated air throughout the home, and hence can activate SBS. If the HVAC system does not effectively distribute

air to people in the building for some reason, there is inadequate ventilation and hence poor IAQ results [6]. In fact, older office-HVAC systems were designed for 'one person per 1500-2000 cm^2, and a PC on every third or fourth desk' and in a modern office with higher occupant densities, it is 'for more people in much less space'. Today's standards require approximately 10,000 litres per minute of outside air per person.

Plants are found to improve and cleanse the indoors air from a number of harmful pollutants such as formaldehyde, benzene and trichloroethylene, as shown in a NASA study [5]. Golden pothos, philodendron, corn plants and bamboo palms are found to be effective in cleansing the air from formaldehyde. *Spathiphyllum* (Peace Lily) and *Dracaena deremensis* 'Janet Craig' are good for removing quantities of benzene, such as tobacco smoke. Trichloroethylene is very effectively removed by *Dracaena marginata*, *Dracaena warneckei* and *Spathiphyllum*. It is recommended by the Plants for Clean Air Council, that one potted plant for each 1,000 cm^2 of floor space is needed for better IAQ [5, 7].

12.1.2.2 Four Elements of SBS

In general, there are four elements of SBS, which may act separately or in combination:

(a) Inadequate ventilation which occurs when heating, ventilating, and air conditioning (HVAC) systems do not effectively distribute air to people in the building, as discussed previously.

(b) Chemical contaminants from indoor sources: are the predominating direct source of indoor air pollution. Adhesives, carpeting, upholstery, manufactured wood products, various construction materials, in addition to copy machines, pesticides, and cleaning agents that all emit VOC. If coupled with poor ventilation, they can create poor air quality which is believed by adherents of SBS to either create health problems or increase existing ones.

(c) Chemical contaminants from outdoor sources: are more indirect than indoor contaminants. Pollutants such as motor vehicle exhausts can be conveyed indoors through air intake vents, doors, and windows.

(d) Biological contaminants: are bacteria, moulds, pollen, and viruses. These contaminants may breed in stagnant water that accumulates in duct work, humidifiers, and the like, or where water has collected on ceiling tiles, carpeting, or insulation. Insects or bird droppings, too, can be a source of biological contaminants. Physical symptoms related to biological contamination include cough, chest tightness, fever, chills, muscle aches, and allergic responses such as mucous membrane irritation and upper respiratory congestion.

Most of the chemical contaminants from indoor sources (the second factor listed) can be avoided by selecting proper safer materials in construction. Commonly, plastics materials (hence all synthetics) are blamed for the source of chemical contamination indoors, and 'natural' construction materials are presented as safe and 'green' [8, 9]. However, a number of natural materials can also contain VOC and hence pose hazards to health as well. Radon is one such material, it is found naturally and it is radioactive and exists almost everywhere in the house, asbestos is another such material. In addition, allergic reactions to the odours from cedar furniture are very common. The reality with plastics is that, it is not the plastic itself that can cause contamination, but the additives used with it, and a careful selection of the material will avoid such problems. And the risk is still always low if a certain agent remains in the building product that does not affect occupants through respiration and physical contact. Certainly, products that give off gas a little are preferable to those that give off gas a lot, and less toxic alternative materials should be used whenever possible.

There are studies to model SBS in residential interiors depicting the relationship between common health problems and factors leading to SBS [10].

12.1.3 Volatile Organic Compounds (VOC)

12.1.3.1 Possible Sources of VOC

A volatile compound is a material that at ambient temperatures or under the influence of heat is capable of being vapourised or becoming a gas, i.e., solvents involved in paints. Some materials indoors may continue to generate VOC over many years (ageing), the concentration of which varies with time, variation in temperature, airflow and volume of the house. Possible sources of VOC indoors are outlined in Section 12.1.2.2.

12.1.3.2 Some Toxic Chemicals that Can be Found Indoors

Table 12.1 presents some toxics that can be found indoors originating from construction materials, and in **Table 12.2**, their effects on humans are presented, followed by some more information about radon and endocrine disrupters (ECD).

Table 12.1 is a general list of some toxic compounds that are commonly found indoors, due to construction materials [19]. One should consider the fact that each indoor space is unique and a specific indoor space may have different toxic chemicals compared to another space.

As an exception, 'radon' is added to the list because of its importance, however, it is still not well known yet. Although radon is not directly related to construction materials, it exists in houses and it can be eliminated by certain construction techniques.

Table 12.1 Some toxics that can be found indoors	
(a)	Radon (a naturally occurring radioactive gas; leaking from basements, crawl spaces and water supplies)
(b)	Formaldehyde (mainly from particleboard and furnishings) and other aldehydes
(c)	Other VOC (emitting from carpets, paints, cleaners, furniture, adhesives, etc.), such as: • Aliphatic hydrocarbons, mainly hexane • Halogenated aliphatic hydrocarbons, mainly chloroform • Aliphatic alcohols, i.e., methanol, ethanol and 1-butanol (found in natural and synthetic resins, paints and lacquers) • Glycols and glycol ethers • Aromatic hydrocarbons, mainly benzene, toluene and xylene (found in paints, adhesives and pesticides) • Various ECD (certain additives and plasticisers)

Table 12.2 The health effects of some toxics found indoors	
(a)	**Benzene**: Mainly causes dizziness, headache, vomiting, drowsiness and unconciousness at low doses. Chronic exposure: if in contact with the eyes: neuritis, atrophy, visual impairment, oedema and cataracts, it can cause depression, bone marrow depression, leukemogen headaches, anorexia, nervousness, weariness, anaemia, pallor, reduced clotting, marrow damage and finally leukemia. Deliberate inhalation of benzene vapours (glue sniffing) can kill directly.
(b)	**Chloroform**: Chronic exposure: can cause liver, kidney, nervous system disorders and heart damage, it is a carcinogen and gives rise to alteration of genetic material (please see below for ECD), fertility problems, foetotoxicity and the following developmental problems: craniofacial, musculoskeletal and gastrointestinal.
(c)	**Radon**: Radon is a highly unstable radiactive gas of natural origin that tends to accumulate in buildings and can pose a serious risk to the health, causing lung cancer, if its concentration is high [11-13]. For more detailed information about radon indoors, please see Section 12.1.6.
(d)	**Endocrine Disrupters (ECD)**: These are chemicals that can cause 'hormonally related diseases, mostly related to reproduction' and 'dysfunction' that can be effective even at parts per trillion levels. A wide range of chemicals, both natural compounds and synthetic chemicals (including certain additives and plasticisers used in plastics) are suspected ECD agents. More detailed information is presented on this subject in Section 12.1.7.

12.1.3.3 Permissable Limits for VOC Indoors

As far as the permissible limits of VOC concentration indoors are concerned, there is hardly any universal regulation established, i.e., in the USA there is no such federal regulation existing, however, several regulatory agencies such as the EPA and the Occupational Safety and Health Administration (OSHA) have worked on developing several standards. However, these are not easy to apply because correlation between methods and indoor VOC concentrations is not straightforward, in addition to the fact that detection of specific low concentrations of VOC may not indicate whether there will be long-term negative health effects or not. However, it would still be essential to have VOC emission information for any material that is to be used in construction to make proper decisions on which materials best meet the requirements while fulfilling structural and aesthetic needs.

In a comprehensive study for IAQ and SBS qualities of office buildings selected in USA [14], it was reported that total VOC (TVOC) ranged from 73-235 $\mu g/m^3$ where the most prevalent compounds were heptane, limonene, 2-propanol, toluene and xylene. Geometric mean formaldehyde concentrations were found to range from 1.7 to 13.3 $\mu g/m^3$ and mean aldehyde levels from < 3.0 to 7.5 $\mu g/m^3$. The prevalence of upper respiratory symptoms (dry eyes, runny nose), symptoms of central nervous system (headache, irritability) as well as musculoskeletal symptoms (pain and stiffness in neck) were found to be high within the workers. While in another study done in Japan to assess the impact of office equipment on the IAQ, it was found that the emission of ozone and organic volatiles (mainly formaldehyde followed by lesser amounts of other volatile aldehydes) emitted are in significant quantities [15]. In one application, in the Washington State East Campus Plus project, office furniture systems were required to emit no more than 0.05 ppm formaldehyde and 0.50 ppm total VOC to be considered for installation. In an another study in Finland [16], estimation of the impact of office equipment on IAQ was questioned and the emission of ozone and various organic volatiles was found from photocopiers and laser printers. The laser printers equipped with traditional (corona rod) technology were found to emit significant amounts of ozone and formaldehyde, with lesser amount of other volatile aldehydes and it is suggested that these are not to be placed beside or immediately at the working site of office personnel.

To give some more depth on this subject, some basic concepts in toxicology and toxic compounds need to be considered. They are summarised in Section 12.1.4.

12.1.4 Toxic compounds and Toxicology

Toxics are the chemical and physical agents that have adverse effects on living organisms, and toxicology is the science dealing with toxic agents. The word 'toxic' may be considered to be synonymous with 'harmful' in regard to the effects of chemicals [17].

A poison is any agent capable of producing a deleterious response in a biological system, seriously injuring function or producing death [18]. Hence, a poison is a substance which by chemical action and at low dosage can kill or injure humans or mammals. The most important factor that influences the toxic effect of a specific chemical is the dose. Almost all chemicals are toxic at sufficient dosage. Paracelsus (1493-1541) phrased this as: 'all substances are poisons; there is none which is not a poison. The right dose differentiates a poison and a remedy'. The strength or potency of poisons is most frequently measured by the lethal dose.

Dose is the number one factor in toxic effect determinations. From statistically treated dose-response data, the dose (in mg/kg body weight) killing 50% of the sample population is designated as the median lethal dose (MLD or LD_{50}). However, one should keep in mind that, LD_{50} values may not accurately reflect the full spectrum of toxicity or hazard all the time, because some chemicals with low acute toxicity may have carcinogenic (or endocrine) effects even at very low doses that produce no evidence of acute toxicity at all.

Another significant factor that influences the toxic effect of a specific chemical is the route of exposure (inhalation, ingestion or skin contact). In general, substances are absorbed into the body most efficiently through the lungs, so that inhalation (which is the case indoors for SBS) is unfortunately often one of the most serious routes of exposure to the poisons, and this route of exposure is our main interest for construction materials. Toxic gases are absorbed by inhalation whenever VOC are released by out-gassing from building materials. The absorption of the toxic chemicals (toxicants, named by Paracelsus) after inhalation occur first in the nose then in the lungs. The nose acts as a 'chemical scrubber' for water soluble and for highly reactive gases, i.e., formaldehyde. Gas molecules diffuse quickly (three-quarters of a second) into the capillary network in the lungs and dissolve into the blood and are then carried to the rest of the body.

Some toxic agents can also be absorbed by the skin. Since skin is permeable, toxic gases can be absorbed and can be distributed by the blood stream quickly through skin penetration. Cuts and other abrasions can accelerate the absorption process.

There is a third factor: the fate of the chemical after the organism is exposed to it. The chemical absorbed can be altered or metabolised (by either being broken down into products that can be incorporated or excreted or by producing less toxic chemicals, called detoxification). The chemical and its metabolites can be excreted, stored or transported in the organism and may, therefore, reach sites where toxic effects are induced, (i.e., by concentrating in a specific tissue, such as liver, kidney or fat). Rapidly excreted substances are generally of low toxicity, and those that are excreted more slowly have the potential to cause long-term effects. Many substances that are stored in the body, mainly in fat or bone, can circulate throughout the organism for a long time.

If a chemical is completely excreted, then succeeding doses have no increased effect, but if a residue remains, then it is possible for the second dose to add to the first and, if doses are repeated often enough, to reach a level high enough to be toxic. In this context, it is obvious that, the water solubility – tissue reactivity and blood to gas phase partition coefficient values of the toxicants are all important in cases of exposure to gases indoors.

It is also worth noting the differences between acute toxicity (effects that occur shortly after a single exposure) and chronic toxicity (delayed effects that occur after long-term, repeated exposures).

12.1.4.1 Classification of Toxic Effects

As far as classification of toxic effects are concerned, there may be five general groups to consider:

(a) *Independent Effect*: Substances exert their own effect being independent of each other, in the case of existence of a combination of toxins.

(b) *Additive Effect*: Materials with similar toxicity produce a response equal to the sum of the effects produced by individual material.

(c) *Antagonistic Effect*: Materials oppose or interfere with each other's toxicity.

(d) *Potentiating Effect*: One material enhances the toxicity of the other.

(e) *Synergistic Effect*: Two materials produce a toxic effect greater than the sum of the two individual toxicants.

12.1.5 Carcinogens

Carcinogens are the chemicals capable of inducing malignant neoplasms. They are substances that induce unregulated growth processes in cells or tissues leading to the disease called cancer. They can be a number of organic and inorganic chemicals with various biological actions, such as, alteration of endocrine system or immuno-suppression. Although carcinogenic chemicals, at least in principle, act in a similar way to other toxic agents (carcinogens show the similar classical dose-response relationship existing in toxic chemicals), carcinogens also show several distinct differences and hence they are described as a 'specialised field of toxicology'.

It is known that, cancer is one of the three leading causes of death in most countries. The association between the exposure to soot and coal tars and cancer was identified in the late eighteenth century after observation of the incidence of cancer patients among chimney sweeps in the UK. Later, the carcinogenic potency of tar was related to its polynuclear aromatic hydrocarbon structure.

Carcinogens can be separated into two general classes based on their chemical and biological properties:

(1) *DNA-reactive carcinogens*: most of the human carcinogenics are of this type. They are active with a single dose, and often such toxic effects are cumulative. They can act synergistically with one another.

(2) *Epigenetic carcinogens (EGC)*: plastics and asbestos are in this group. They are 'genotoxic' (that is they are not DNA reactive and appear to operate by the production of other biological effects)

12.1.6 Risk Management

Since any material must be 'assessed' in the context of the system, there are no truly benign materials and nothing is risk free and 'risk can be managed', i.e., a toxic material can provide significant benefits and may pose little risk 'when used properly': Use of damp-proofing on the exterior of a preserved wood foundation that has an inherently toxic chemical may provide a decreased risk to the occupants [9].

Overall risk assessment rests on three factors:

(a) exposure assessment,

(b) toxicity assessment, and

(c) dose-response assessment.

Exposure assessment is a necessary component in understanding the hazard involved by exposure to naturally, i.e., radon, or non-naturally existing toxicants, chemicals emitting from construction materials [19]. However, the other two (toxicity and dose-response assessments) are the next two important factors to know.

12.1.7 Radon Indoors

Radon is the biggest possible contribution to radiation exposure in houses (50%) that occurs naturally [13]; and as a gas, it has no taste, smell or colour. Radon exists

everywhere but it is usually in insignificant levels that pose negligible health risks. It is a radioactive decay product of uranium (over radium). Since uranium is found in all soil and rocks usually in small quantities varying from place to place, radon also exists and in varying quantities.

Due to the effects of wind and temperature, the air pressure inside a house is usually lower than the air pressure in the soil beneath it and air containing radon from the soil creeps into the lower pressure area of the house (through cracks and gaps in the floor or walls). When radon rises from the soil to the air, outdoors, it is diluted enough, however, when it enters enclosed spaces, high concentrations can build up indoors with a serious risk to health. Especially in air with already high levels of radon, indoors, concentrations can rise up to very high dangerous levels easily.

Radioactive decay of radon forms particles called 'radon daughters' which, after inhalation, can damage lung tissues leading to cancer [20].

12.1.7.1 On Indoors Radon and Measurement of its Concentration

Radon gas concentrations are measured in becquerels per cubic metre (Bq/m^3), and the level of 200 Bq/m^3 (maximum) is considered as the action level for homes. This value is double for offices, because usually more time is spent in the home than at work. The level of radon observed normally is 1/10th of the action level (20 Bq/m^3). In a study done in the UK, it is shown that levels of radon varies considerably from location to location on site with the possibility of reaching values well above the action level suggested (called 'high radon potential areas') [21]. One should realise that radon is not a problem of basements only, but it can exist even on the upper floors of high rise buildings. In an experimental study, indoor radon levels were monitored continuously with and without air-conditioning in a number of high-rise office buildings in Hong Kong [22], and it was found that the average indoor radon level during office hours were not as low as expected from the high rise positions (they were between 87-296 Bq/m^3 with ventilation, which was some 25% lower than without ventilation). The average radon emanation rates were found to vary between 0.0019-0.0033 Bq/m^3 for different high rise buildings and it was estimated that building infiltration rate accounted for about 10-30% of the total building ventilation rate in the buildings depending on building tightness [22, 23]. On the contrary, there are also reports claiming that sealing homes to save energy does not concentrate radon indoors [22, 23].

Radon levels indoors can be measured by a safe and a rather simple method by use of detectors, one in the living room and another in an occupied bedroom. In one experiment (in UK), the detectors used are just a piece of spectacle lens plastic put in a protective shell, about the size and shape of a small door knob (obtainable through mail order in some

countries [24] and which are returned after three months of test in the reply paid envelope provided). The plastic in this system records radon which is measured by accredited laboratories after its return. There are also much shorter, (i.e., fortnightly) measurements available, however, they are less accurate, that can be used for screening purposes as well [24].

Indoor radon measurements obtained for homes in North Virginia, USA, revealed that existing high or low median indoor radon levels in each house persist through four seasons [25], however, attempts to compare the soil radon and soil permeability was not successful.

12.1.7.2 Some Measures to Prevent Radon Accumulation Indoors

There are several studies showing the main defects in design and implementation to avoid high radon indoors and to give guidance on radon-safe buildings in slab-on-grade houses [24, 26, 27]. It is certainly best to stop radon entering the house first, and if this is impractical, then effective removal (or dilution of it) is recommended. It is shown that there are several ways to achieve these [24, 26]. The prevention (or decrease) of the flow of radon-bearing air indoors can be done through installation of aluminised bitumen felt as well as by use of elastic sealants – to seal cracks and gaps in solid concrete floors and walls. As a precaution, it is suggested that perforated piping is installed in the subsoil of the floor slab. There are a number of studies such as on sub-slab ventilation matting [28], as well as production of alpha particle radiation barriers of sulfopolyester-acrylic copolymer [29], and polyamide/polyester matting [30] and others [31, 32].

Installation of a radon sump system equipped with a fan is suggested as the most effective and best choice for high levels of radon [24]. For this, a sump which is a small empty space about the volume of a bucket is dug under the solid floor and a pipe is routed from it to the outside air. The sump and the fan connected at the exit of the pipe to suck out air, both help to alter the air pressure below the floor and to release it harmlessly into the atmosphere. There are also applications where the fan is replaced by a blowing system to facilitate removal of the remaining radon in the soil. It is also possible to increase the circulation of air beneath the floor (improved ventilation under suspended timber floors with or without a fan via air-brick) or at loft level or even by using positive house ventilation as a whole ('positive pressurisation' is most effective if the house is very air-tight). All of these are common methods that have been suggested and applied.

12.1.8 Endocrine Disrupters (ECD)

As outlined previously, ECD are chemicals that can cause 'hormonally related diseases' and 'dysfunction' that can be effective at very low levels (even at parts per trillion levels

at which most chemicals have never been tested). ECD has become a significant focus of environmental science and medicine in recent years.

A wide range of chemicals, both natural compounds and synthetic chemicals (including certain additives and plasticisers used in plastics, in addition to well known pesticides such as dichlorodiphenyltrichloroethane (DDT) and many industrial and consumer products, liquid soaps, shampoos, conditioners, and hair colours – that contain alkylphenol ethoxylates (APE), polychlorinated biphenyls (PCB), dioxins, certain preservatives and metal ions, even certain woods, are all now suspected of causing endocrine disruption in humans. In the EU, the products with APE have been replaced by the more expensive, but much safer, alcohol ethoxylates.

Some 'endocrine disruptors', phytoestrogens, occur naturally in a variety of plants. Living things evolved with them, they are metabolised or degraded so that they do not bioaccumulate. Of current concern are the synthetic estrogens produced either through industrial manufacture or as by-products of such processes or burning. Those we know about have been identified by laboratory tests such as those that measure a chemical's ability to speed the growth of cultures of breast cancer cells.

The mechanisms of ECD is poorly understood and specific end points or effects of ECD are not clearly defined yet, and there is still much to be understood and to be explored about its role.

12.1.8.1 Suspected ECD Agents

There are four groups of chemicals that are labelled as 'suspected ECD Agents':

(a) Certain plastics additives,

(b) Certain PCB,

(c) Chlorinated dioxins and dibenzofurans, and

(d) Certain metal and metal compounds.

Plastics Additives (Mainly Plasticisers)

Plastics contain various additives, such as phthalates, bisphenol-A, and nonylphenols, usually present as plasticisers used to make them flexible and durable. They can leach out into liquids as well as evaporate into the gas phase and can be inhaled. Increase in temperature usually speeds all of these (which is why microwaving foods in plastic is discouraged). Oestrogenic butyl benzyl phthalate is found in vinyl floor tiles, adhesives,

and synthetic leathers. Its relative, dibutyl phthalate is present in some food-contact papers. Bisphenol-A is a breakdown product and plasticiser of polycarbonate plastics, which is mainly used as a glazing material.

The EU decided that the year 2002 was the key milestone to complete risk assessment of phthalates [33].

For more detailed information about certain plastics and plasticisers and their effects on health, please see Section 12.2.2.1 [Thermoplastic construction materials (polyvinyl chloride (PVC), polymethyl methacrylate (PMMA), polyethylene (PE) and polycarbonate (PC)] and the plasticisers part of Section 12.2.2.1 (Additives).

In addition to plasticisers, there are a number of different additives used for different purposes, i.e., stabilisers used in PVC window profiles and pipes are mostly lead-based, or they can be either barium/cadmium/or zinc compounds. All of these can pose a health hazard if they migrate out of the system above certain concentrations.

PCB

PCB are a family of toxic, oily, non-flammable industrial chemicals, commercialised in 1929 by Monsanto. Although their production in the USA was stopped in 1977, world production still continues. PCB are still present in the USA in certain (old) electrical equipment and frequently found at toxic waste sites and in contaminated sediments. Recently it was confirmed that children exposed to low levels of PCB in the womb because of their mother's fish consumption grow up with low IQ, poor reading comprehension, difficulty paying attention, and memory problems.

A Swedish study showed that there may be high levels of PCB around some old buildings in which sealants containing the chemicals were used some 20-40 years ago. These sealants based on polysulfide polymers were used from the 1950s for filling external joints in buildings and until the late 1970s and they may have contained up to 20% PCB. In the study, a very high PCB level about 100 times the typical ambient levels in Stockholm was measured on a balcony on a hot summer day. Although these sealants are normally not used inside buildings, the study found one exceptional case where there were high levels of PCB in the stairway of a building too. The report recommends checks on PCB levels in all structures built between 1956-1972. PCB sealants have also attracted attention in USA, UK and Germany, but no research or monitoring is in effect in any of them. PCB in many polysulfide sealants have now been replaced by chlorinated paraffins which are also have certain restrictions raised within the Oslo and Paris commission [34, 35].

Chlorinated Dioxins and Dibenzofurans

The term 'dioxin' is commonly used to refer to a family of compounds comprising around 75 dioxins and 135 related furans. The number and position of the chlorine atom differs for each of these compounds and also has a considerable effect on their relative toxicity – 17 of them are recognised as highly toxic. Chlorinated dioxins (PCDD) and dibenzofurans (PCDF) are within this group, and they are by-products of chlorine bleaching of paper, the burning of chlorinated hydrocarbons such as pentachlorophenol, PCB, and PVC, the incineration of municipal and medical wastes, and natural events such as forest fires, traffic exhaust and even volcanic eruptions. They often contaminate toxic waste sites, especially where there have been fires. They bioaccumulate in fish and other wildlife and the most common human route of exposure is through the food chain. The International Agency for Research on Cancer has classified the dioxin 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD) as a known human carcinogen.

Metals and Metal Compounds

Although all living organisms require certain metals for physiological processes, when they present at concentrations above the level of homeostatic regulation they can be toxic. Metals can exert toxic effects directly on the functional groups in enzymes either through altering the conformation of biomolecules or through displacement of essential metals in metalloenzymes.

The most common metals and metal compounds that can be found in the atmosphere indoors are antimony, lead, methyl mercury and cadmium. These metals, their organic metal compounds and metal ions that can exist in plastics as additives used for different purposes are believed to disrupt the endocrine system by causing problems in steroid production. The fate of these metal and metal ions, mostly found and used as stabilisers, has been more extensively studied for the lead and lead-based compounds, however, much less for the others.

(a) *Lead (Pb):* Lead has no biological role and it is a cumulative poison. The most serious adverse effects, mental retardation and learning problems, occur in young children subjected to chronic exposure, most often through ingestion of paints. All forms of lead are extremely toxic to humans. Children with iron and calcium deficiencies absorb more lead and hence there is greater adverse effect. The main effect on adults is also neurological. The initial symptoms of mild lead poisoning are headaches, nausea, stomach pains, vomiting, joint pain and constipation. At higher exposure levels, there is toxic psychosis. It can cause hypertension, anaemia, neurological effects (especially in children), kidney damage, digestive problems, sterility, miscarriages, and possibly cancer. A single dose is unlikely to kill, but its absorption over a period of time is fatal. It is locked away in the bones as lead phosphate.

Soluble lead can leach from old water pipes, badly glazed pottery and even from lead crystal decanters. In a study, it was shown that the rate of lead extraction from a 100 mm diameter PVC wastewater pipe system was 0.7 μg/l/day [36] and that sewer systems can contribute 0.5 μg/l lead to the wastewater [37]. On the other hand, in the CSIRO report it is concluded that, 'under normal use conditions in the potable water industry, the level of lead extracted from properly commissioned PVC pipe has been found to be below the levels of detection' [37]. Some old paint may also contain lead. Lead or lead compounds are absorbable by the body and also by inhalation. If the amount absorbed is small, the body can get rid of some of it through urination, but some may still stay in the body stored mainly in the bones and can stay there without any poisoning effects until a certain dose is reached by accumulation in time [38].

The EU put forward following key milestones as regards to control and diminishing the use of lead stabilisers in plastics: by the year 2004, completion of initial risk assessment on lead stabilisers will be accomplished; by 2005: 15% (to reach 100 Kt), and by 2010: 50% reduction target of their use (reaching 60 Kt), and by 2015, it will be 100% off for use of lead stabilisers [33].

(b) *Antimony (Sb):* although it has no biological role, antimony is toxic. It cannot be excreted from the body and large doses cause copious vomiting and liver damage. Antimony is used as a flame retardant additive (mainly for PVC). During the 1990s, antimony containing PVC was accused of causing cot deaths in babies (it is claimed that antimony is converted to the volatile toxic gas, stibine (SbH_3) by a fungus existing in the mattress). However, this claim is not proved so far and although the analysis of tissue from cot death victims had antimony levels somewhat higher than allowed, 13 ppm, similar results are also observed for healthy babies. Moreover, in the house dust of some old houses the level of antimony can already exceed 1800 ppm, the source of which is not known exactly [24, 39].

(c) *Arsenic (As):* Arsenic is a deadly poison with a lethal dose of 100 mg. It is the third metal most often implicated in human toxicity. The valence form of arsenic is critical to its toxicity, trivalent arsenic (as in arsenic trioxide) is the most toxic. The symptoms of arsenic poisoning are vomiting, colic, diarrhoea and disturbances of the haematopoietic and central nervous systems, progressing to coma which leads likely to a heart failure [24]. Chronic exposure is associated with cancers of the skin and lung and may be linked to cancers of internal organs.

In houses, the source of arsenic can be from paintings (the bright yellow pigment, called 'royal yellow' is in fact 'orpiment', or arsenic trisulfide chemically); which was favoured by Dutch painters in the near past. This paint slowly oxidises to arsenic trioxide, which is very toxic, by fading in colour. Arsenic is also used in treated lumber (wood).

The arsenic allowed under the EPA's proposed drinking water standard is a maximum of 10 parts per billion.

(d) *Cadmium (Cd):* Cadmium is an accumulative poison. If its level exceeds 200 ppm in the body, kidney failure and damage develops and its further increase weakens the bones and joints (most probably leading to cancer). Exposure to high levels over short periods of time leads to nausea, vomiting and cramps.

Cadmium is used as a common bright pigment (cadmium yellow) in the form of cadmium sulfide in paints, rubber and plastics as additive. Until recently, cadmium red was widely used for containers, toys and household wares but has now been phased out completely. The EU put forward March 2001 as the key milestone to end sales of any cadmium containing stabiliser [33].

(e) *Phosphorus (P):* As a poison, phosphorus attacks the liver quickly. Breathing phosphorus vapour over a long period of time can lead to the disease known as 'phossy jaw', which slowly ate away the victim's jaw bone. Phosphorus containing compounds are used as flame retardants (specifically in the synthetic fibre industries, such as polyester production).

(f) *Tin (Sn):* Tin compounds can be poisonous by ingestion, especially organotin compounds, [(i.e., trimethyl (TMT) or triethyl-tin (TET)]. They can upset various metabolic processes with fatal results in the human body. Organo-tin compounds (with four organic groups attached) are used as catalysts in the production of polyolefins such as polyethylene. Tin (with one or two organic groups) are effective additives used to decrease heat sensitivity of plastics (as organotin stabilisers), i.e., for PVC.

Tin (with three groups attached, such as TBT) are widely used as wood preservatives and anti-fouling paints, as well as to prevent unwanted growth of moulds on stone structures.

(g) *Zinc (Zn):* Zinc is generally labelled as non-toxic, however, excess can be stored in the bones and spleen. The most significant toxic effect of zinc is fume fever, that can result from acute inhalation of zinc oxide fumes.

Zinc oxide is used largely in the rubber industry (acting as a catalyst during manufacture and as a heat dispenser in the final product) as well as in pigments for plastics and wallpaper. It also functions to prevent the UV damage of the plastics and rubber.

In addition, there may be mercury vapour emitting from biocides used in paints.

12.2 Construction Materials and Health Issues Indoors

Some of the ingredients, mainly additives existing in various construction materials can slowly evaporate and/or breakdown, releasing different chemicals. Of all the construction materials, plastics and wood are our main concern in this chapter. It is essential to see their possible VOC contributions briefly.

12.2.1 Plastics

In the plastics construction materials list, the biggest share belongs to PVC (55%), as followed by polystyrene (PS, 15%), polyolefins (15%), polyurethanes (PU, 8%), and others, mainly PMMA (7%) [24]. These plastics are used in different applications in construction and they are usually blended with certain additives. These additives cause the main toxic effects of construction materials.

12.2.1.1 Additives in Plastics

Additives are materials that are blended with polymers to make them easy to process and to give them certain physical properties for specific applications as well as to protect them from the effects of time, heat and environmental conditions. Additives play a key role in improving and creating the unique performance characteristics of plastics. Usually, additives are stabiliser systems to ensure durability and plasticisers to produce a degree of flexibility, in addition to other additives, (i.e., pesticides and antimicrobials, lubricants, pigments, flame retarders, impact modifiers, antistatic agents, UV absorbers, compatibilisers). Being smaller in size in general than the parent polymer, and being organic molecules, migration and even sweating of the additives can occur which results their vapourisation and hence emission of their toxic effect into the vapour phase which can then be inhaled by humans. There are ongoing studies to bond the additive to polymer backbone to blockade and hence control the migration.

Pesticides and Antimicrobials: Pesticides and antimicrobials (biocides) are used in construction materials to provide resistance to the growth of microorganisms – such as bacteria, fungi and algae (used mostly for PVC and PU grades, the latter for roofing membranes) [40], because some ingredients (several plasticisers, lubricants, thickening agents and fillers) can support their growth. Use of these materials in contact with high humidity can activate microbial attack. Some commonly used plasticisers (dioctyl phthalate, diisooctylphthalate, dibutylphthalate, tricrescyl and triphenyl phosphate are the most resistant to microbial attack. The major antimicrobial agents used in PVC are 10-10′-oxybisphenoxarsine (OBPA), *n*-(trichloromethylthio) phthalimide and 2-*N*-octyl-4-isothiazolin-3-one (OITO).

Stabilisers: Stabilisers are added to plastics to afford protection against thermal and UV degradation of the polymer during processing and use, respectively. Some thermal stabilisers also have an activating influence on the blowing agent. The commonly used stabilisers for PVC are compounds of lead (basic lead sulfate and lead stearate: they are relatively low cost), tin (mono-and dibutyltin as well as thioglycolate: with excellent thermal stability and very low toxicity), cadmium, and complex salt systems of barium/zinc and calcium/zinc. Within these, it is known that all forms of lead are extremely toxic to humans because of their cumulative effects. Metallic tin is harmless but organotin compounds can be toxic to the central nervous system and the liver. Cadmium causes kidney damage and anaemia and phasing out of cadmium containing heat stabilisers is underway. Calcium and zinc systems are non-toxic to humans, they can offer comparable properties but at a higher cost. Lead systems, although considerable toxicity may result, are still expected to remain the dominate stabiliser type until legislation dictates otherwise. The fate of heavy metal stabilisers are dependent on a number of complex factors, but never the less, since the stabiliser is held within the plastic matrix only limited losses from the surface of the bulk is expected.

Recently some organic-based stabilisers with a pyrimidinedione system with no heavy metals were introduced and they found immediate use.

Hindered amine light stabilisers (HALS) are the main stabiliser type (as a scavenger to inhibit free radical chain propagation) in addition to organo-nickel compounds (as a quencher to prevent initiation of polymer degradation) are used for UV stabilisation.

Plasticisers: A plasticiser is an organic compound which when added to a plastic makes it flexible, resilient and easier to handle. They may function either 'externally' or 'internally' in their preparation and action. The most common type, which also fits mostly to the general definition used above, is 'external'. Internal plasticisation is accomplished by structural groups incorporated chemically onto the polymer chain through a plasticising comonomer. On the other hand, plasticisers can be classified by their function, as 'primary', 'secondary', 'extender', 'general purpose', 'high/low temperature', 'non-migratory', 'fast fusing', and 'low viscosity' [41].

In early applications, oils were used to plasticise pitch for waterproofing ancient boats. However, modern plasticisers are usually man-made organic chemicals and are externally used. They are mostly esters, such as adipates and phthalates, that have been in use for about 50 years. There are more than 300 different types of such plasticisers and 100 of them are in commercial use. The PVC industry, because of its industrial status makes the largest usage of plasticisers, and dominates the literature on plasticisers. These PVC plasticisers are mainly phthalate esters of C_8, C_9 and C_{10}. They are used to make flexible PVC, mostly used in flooring products to make them easy to roll, store and install.

Although these plasticisers have low volatilities, there is still a probability of their emission occurring and subsequent accumulation indoors in time, in addition to their inclusion in household dust as vinyl floor surfaces are abraded in use. About one million tons of plasticisers are used annually in the EU, mainly in the plasticisation of PVC.

The first adverse publicity on plasticisers was in the 1980s for one of the phthalates, dibutyl phthalate (DBP), when it was shown that the vapour emitting from plasticised PVC (PVC-P) glazing seals could damage certain greenhouse crops. In fact, phthalates were the first known to cause liver tumours in the 1980s after a three year study done by the National Toxicology Program in the USA on di-(2-ethyl hexyl) phthalate (DEHP), also known as di-octyl phthalate (DOP). A short term (or subchronic) effect of DEHP is enlargement of the liver. Studies, however, have shown that, DEHP alone does not cause this hazardous effect. In fact, in one study in Japan, it is shown that high densities of a number of chemicals are created when DEHP reacts with water. In February 2000, the International Agency for Research on Cancer (IARC) reclassified DEHP alone as 'not classifiable as to its carcinogenicity to humans' [42]. However, the potential effects of DEHP are still under investigation. It should be added that, peak levels of DEHP were traced in sediments of the river Rhine between 1972 and 1978, concentrations in the most recently laid sediments being lower by a factor of six [40].

PVC-P, on average, contains 55 phr (parts per weight per hundred of PVC) plasticiser. PVC has the ability to accept high levels of plasticiser (100 phr and even above). The most common plasticisers that are used today in PVC are DOP (used in the manufacture of flooring and carpet tiles), DEHP (used mainly for any flexible PVC applications), di-isodecyl phthalate (DIDP), used mainly in wire and cable production, carpet backing and pool liners, di-isononyl phthalate (DINP), and butyl benzyl phthalate (used mainly in vinyl tile production), and di-*n*-hexyl phthalate (used in flooring applications). There are also several plasticisers that are specific for almost no toxicity, such as tri-(2-ethylhexyl) trimellitate (TEHTM), a polymeric adipate, and acetyl triburyl citrate (ATBC), which are economically unfeasible for their industrial applications, i.e., TEHTM is some three times as expensive as DEHP, and polymeric adipate four times as expensive. Analytical techniques are available to detect traces of plasticisers at the parts per billion level [43].

External plasticisers are not bound chemically to the polymer but they are held by rather weak intermolecular forces in the system, with the capability of migrating to surfaces and hence their evaporation occurs. Since they are organic chemicals with certain levels of toxicity, their effects on health are being questioned. Five phthalates (DBP, DEHP, DINP, DIDP and benzylbutylphthalate (BBP)) are currently undergoing EU risk assessment, however, under the 'European Dangerous Substances Legislation (Directive 67/548/EEC)', no phthalates are classified as carcinogenic. Some plasticisers, mainly certain phthalates, in fact, are found to affect stereoid metabolism by increasing the levels of endogeneous

oestrogens by inhibiting their sulfation, these are known as endocrine disruptors (ECD) [44]. The phthalate plasticiser DEHP was used extensively in PVC floor coverings, however, recently another phthalate, DINP, has been used. Although not proved so far, it is claimed that, even during normal wear and tear of the plastised product, i.e., during washing vinyl floors, phthalates can get into the environment [45]. Recently, DEHP was cleared from being a carcinogenic substance by ECPI (European Council for Plasticisers and Intermediates). It is relevant to note that the often recommended alternative to phthalate plasticisers, di-2-ethylhexyl adipate (DEHA) migrates from PVC products to a substantially greater extent and is also an ECD for mammals. Hence, alternatives to phthalate plasticisers need to be studied in far greater detail before their consideration as appropriate replacement [46]. In any case, the use of adipate, mellitate and azoalate type plasticisers are expected to grow in use at the expense of different phthalate types.

For rubbers, process oils, which are simply hydrocarbons, do plasticise the system.

Polyvinyl acetate (PVAc) (adhesives), as well as cellulose acetate (CA) compounds and sheets, cellulose nitrate pigment binders and polyvinyl butyral (PVB) sheets (used mainly for safety glass interlayers) are other main users of plasticisers.

Polybutenes are applied as plasticisers in butyl rubber-based membranes for roofing systems.

Butene-based alcohols have been primarily used in the manufacture of flexible PVC [47], whereas polycaprolactone is applied as permanent plasticiser for PVC [48].

As mentioned previously, the EU put forward the year 2002 as the key milestone to complete risk assessment of phthalates [33], unfortunately this was not completed and work is still ongoing. Currently, it is known that there is high interest in plasticisers and their effects on health, worldwide and that in the EU, about one million Euro a year is being spent on such research in industry.

Flame Retarders: Flame retarders are used to inhibit or retard the fire. The active retarders of fire are the halogens (by inhibiting free radical formation in the vapour phase, chlorine and bromine being the most effective) and phosphorus (which functions by developing a protective char); and there is a synergy between antimony, zinc and other metal salts. The common flame retarders are mainly hydrates, such as antimony trioxide and aluminium or magnesium hydroxide, alumina trihydrate, zinc borate, phosphate esters and chloro-paraffins. They were mostly developed after the ban on halogen-containing retardants. The ban was because of the toxic nature of halogens and especially their emission to the gas phase when the system is heated, however, the pressure to ban in Europe has abated nowadays. 'Zero halogen' flame retardants are mainly used for cable applications.

Chlorinated paraffins: (mainly chlorinated PVC (CPVC)) are widely used in PVC as they have greater resistance to ignition and combustion than general purpose plasticisers. However, the effects of chloroparaffins on health is still a controversial issue and its use as a flame retarder in PVC applications for cables, wall coverings and flooring are declining [41].

Impact Modifiers: Impact modifiers are either systems with spherical elastomer particles in a rigid polymer matrix or they are systems with a honeycomb, network type of dispersed elastomeric phase. For the spherical elastomeric particles, examples are acrylonitrile butadiene styrene (ABS), methacrylate-butadiene-styrene (MBS) and acrylics. These systems are either graft copolymers of methyl methacrylate-butyl acrylate-styrene or methyl methacrylate-ethylhexyl acrylate-styrene. For the honeycomb, network type of dispersed elastomeric phase ethylene vinyl acetate (EVA) and chlorinated polyethylene (CPE) or directly dispersed rubber are examples. Both of these two impact modifiers exist in the polymeric form, hence they can hardly migrate and evaporate because of their size. As a result, they pose almost no problems to health. For PVC window frame production, usually the first type (and acrylic impact modifiers) are used while MBS modifiers are found to be very effective in plasticised as well as in rigid PVC. CPE is mainly used in PVC for products like sheet, pipe, gutters and sidings.

Others: Lubricants are processing aids and function to ease the process and are of two types: internal (that influence the viscosity, such as calcium stearates) or external (such as oxidised polyethylene wax). Lead stabilised PVC lubricants are a part of the stabiliser system. They are important in the PVC foam formulations.

Processing aids are usually based on high molecular weight acrylic copolymers (for PVC). They modify the rheology and processing characteristics of melt to be processed.

12.2.1.1 Some Thermoplastic Construction Materials (PVC, PMMA, Polyolefins and PC)

PVC

PVC is one of the world's oldest plastics, and it is the most dominant in building and construction. PVC is a tough, strong thermoplastic material which has an excellent combination of physical and electrical properties. PVC is a major plastic material which is commonly used in building (55% of plastics used in construction are PVC), mainly because of its excellent fire performance [49]. PVC is replacing 'traditional' building materials like wood, concrete and even clay. PVC and its copolymers are one of the most versatile and widely used resins in building product applications. The uses of PVC are

many and varied. Its use in the building sector includes piping and pipe fittings (pressure piping for potable water as well as for gas and normal piping for drains and sewerage), cable and wiring covers, electrical switches and conduits, roofing and building membranes, insulation, flooring, wallcovering, trim, carpet fibre and backing, miniblinds and shades, window frames (all vinyl and composite) and doors, partitions. Its exterior uses are sidings, cladding, profiles and coatings, as geomembranes in outdoor landscaping, (i.e., in ponds or to waterproof large areas), and as tensile or stressed fabric structures (in place of conventional roofs and structures of a semi-permanent nature), such as vinyl fence and sound barriers, and in many others. More than 60% of all PVC applications have a life cycle between 15-100 years.

PVC products are usually characterised as either plasticised elastic materials or as rigid types (rigid PVC, or PVC-U). PVC-P are used as shower curtains, floor coverings, in wires and cables, as coatings and as wall covering, etc. Rigid PVC on the other hand, are mainly used in pipe production and in making window and door profiles. Copolymers of PVC are used mainly as filaments for upholstery and window screens, in addition to their use in pipes. PVC pipes are primarily used for urban and construction water supply, and drainage as well as for wire and cable pipe (coatings). One of the major uses of rigid PVC in Europe and the US is as profiles for windows and doors and some 40% of all window profiles in Europe are made from PVC. In addition, the Chinese government banned the use of wooden or iron or aluminium window frames by actively promoting vinyl frames in the country with a target of 20% for the use of vinyl in the construction of new homes. China has became the country with the largest production for windows and doors in the world where plastic windows and frames production has advanced ten times during the last decade [50].

In Europe, plasticised flexible PVC is the key material used in single ply membranes used to cover large flat roofs. For these applications, plasticiser systems used are mostly linear phthalates (mainly due to their low volatility and high photostability).

Cellular PVC, developed during World War II in Germany, is largely used in a number of different structural applications, i.e., closed cell rigid PVC foam, as a structural core in sandwich panels and plasticised closed/open cell soft PVC foam in cushioned flooring, etc. For these, usually air, or chemical blowing agents (carbon dioxide, nitrogen, etc.) are used. PVC production was about 40 kT in Western Europe in 2001. Additional information on PVC is provided in Chapter 2.

PVC and Health Effects: Virgin PVC is thermally and photochemically unstable and has a tendency to loose hydrogen chloride easily when heated, hence a stabiliser (a tin or a lead compound, usually heavy metal based compounds) is commonly used in the final compound to improve the heat stability. Various additives that are used to reduce various

limitations in PVC are inert fillers, heat stabilisers, plasticisers, flame retardants, impact modifiers, smoke retardants, pigments, UV-radiation stabilisers, antistatic agents, bubbling agents and fungicides. Some of these additives can leave the system as a vapour during the use of the PVC material, and since most of these chemicals are toxic, their emission poses several health problems [51, 52].

PVC is produced from its monomer, vinyl chloride monomer (VCM). VCM is highly carcinogenic and can cause liver cancer (in a recent study it is shown that VCM can cause brain cancer [53]). VCM can stay in the polymer in trace amounts after its production, which can stay in the (solid) system in small proportions even after processing the PVC into final shaped products. Maltoni and co-workers first reported that the presence of VCM led to carcinogenicity in animals and linked this to a rare but lethal form of liver cancer (liver angiosarcoma) that was found in a limited number of operators exposed to VCM in PVC plants in the early 1970s [54]. In humans, VCM is known to metabolise into chloroethylene oxide which is believed to have a most potent effect as a carcinogen. However, since 1974, the PVC industry has taken necessary measures worldwide to reduce the VCM intake. The occupational limit for VCM is currently 1 ppm averaged over an eight hour period and 5 ppm averaged over any period not exceeding 15 minutes, with an annual maximum exposure limit of 3 ppm. The 1997 European Pharmacopoeia requires a maximum of 1 ppm of VCM residual in virgin PVC.

PVC is regarded as inherently flame retardant (due to its high chlorine content, 57% in virgin PVC is chlorine) and in most cases PVC-U cannot burn without an external heat source, except the plasticised form of it and for this reason a number of flame retardants are used in its plasticised formulations. When burned, PVC produces 'dioxins', which are known to be a deadly poison and a strong carcinogen. In addition, its smoke gas density is high and releases corrosive and toxic hydrogen chloride gas. A study carried out to examine the possibility of VCM formation during routine PVC thermal welding revealed that atmospheric concentrations of VCM as well as for acetaldehyde, benzene and formaldehyde are well below accepted occupational exposure limits [55]. On the other hand in the UK, it was reported that overheating PVC in a PVC processing plant (through an overheated extruder) caused acute upper and lower respiratory irritation due to toxic hydrogen chloride and carbon monoxide emissions [56].

Health effects of PVC itself and its additives (mainly plasticisers) have been the subject of a very intense debate for many years, beginning from the 'danger of release or extraction of the heavy metal based stabilisers' and 'health implications of phthalate plasticisers and other additives' to 'the danger of formation of dioxins and hydrogen chloride gas during accidental fires'. For many years, there has been a never ending debate between different parties about PVC and its effect on health and on the environment, some are

correct but most of which is speculative and opportunistic. It is interesting to observe that there is no country in the world yet where PVC has been banned as a material, although there exists strong anti-PVC lobbies in certain countries. The details of this debate and discussions are beyond the scope of this book. But nevertheless, by considering the fact that PVC is being used heavily in the health sector, even as blood bags and dialysis equipment tubing, which appears to be a paradox; and that its production and consumption rate increases every year, it should not be difficult to predict that PVC will continue to be the number one plastic for the construction sector for years to come.

In fact, it is known that if the production and use of PVC applications are made carefully, PVC products will be completely safe without any detrimental effects to health or the environment [57].

Greenpeace has launched a site on its web page that even gives suggestions for 'PVC Alternatives' as a database for those seeking alternatives for vinyl products in construction [58]. In fact, there are many alternatives to most PVC building and construction products. However, available evidence indicates that PVC in its building and construction applications has no more effect on the environment than its alternatives. The possible adverse human health and environmental effects of using PVC in building is not greater than those of other materials [57]. Additional studies are still required on certain aspects of PVC due to the either unavailable, inconclusive or even contradictory evidence available, and studies are underway for the clarification of some of the issues surrounding the use of PVC, especially the health effects of the phthalate plasticisers (used to flexibilise) and heavy metals (used as heat stabilisers) as well as the toxicity of the emissions from fires involving PVC.

As a final note, it is worth noting that, there is an EU voluntary commitment study on the PVC industry initiated in 2001 for the following 10 years (called Vinyl 2010), including mid-term revisions of targets in 2005 and definition of new objectives in 2010. The plan includes full replacement of lead stabilisers by 2015, in addition to the replacement of cadmium stabilisers by March 2001 [33, 57]. In addition, in the same EU proposal (Vinyl 2010 [33, 34, 35]) the following values are proposed for maximum permissible VCM concentrations acceptable in the final PVC products:

For suspension type PVC: maximum VCM: 5 g/ton of PVC (for general purpose) or 1 g/ton of PVC (for food and medical applications), and for emulsion type (E-PVC), maximum VCM: 1 g/ton of E-PVC.

In the same study, the year 2002 was put forward as the key milestone to complete phthalate risk assessment [33] this was partially completed and is still ongoing.

On the other hand, by the use of 'internal plasticisers' where the plasticiser is incorporated (usually by grafting) onto the polymer chain of PVC (see Section 12.2.2.1)

or by use of special plasticising polymers, problems associated with migration are minimised or even eliminated completely. Different types of plasticising polymers (with less danger of migration) for PVC are suggested, such as, EVA terpolymers, ethylene-acrylate terpolymers and nitrile rubber blends, although economy of their use is not too favourable [41].

Polycarbonates

The building block for polycarbonate (PC) is bisphenol-A (BPA). It is a tough, durable, shatter and bulletproof, and heat resistant, perfectly transparent, easily mouldable and dyable engineering plastic and it is ideal for a number of applications for creating functional and aestetically pleasing products. The first audio compact disc (CD) introduced in 1982 was made of PC, followed by compact disc - read only memory (CD-ROM) within 10 years and within 15 years digital video disc (DVD). All of these optical data storage systems depend on PC. PC are being extensively used for transparent roofing, impact-resistant glazing and sheet (about 32%) and for structural parts in building and construction. Green houses and the dome of the Sydney Olympic stadium are all PC sheet glazing. PC sheets are virtually unbreakable (bullet resistant windows, protective PC glazing panels). PC resins and BPA are known to be safe and they pose no health risk to humans.

BPA exhibits toxic effects only at very high exposures and realistically, such high exposures are not possible under normal conditions indoors. BPA is not a carcinogen or a reproductive or developmental toxin.

Polyolefins

Polyolefin is a generic term for polyethylene (PE) and polypropylene (PP). The burning of these plastics can generate several volatiles, including formaldehyde and acetaldehyde, both of which are suspected to be carcinogens.

Polyethylene is the second oldest and the most common commodity plastic. Within the three different versions of PE, there are:

(a) *Low Density Polyethylene (LDPE)* covers all types of PE with densities 0.940 or less excluding copolymer grades marketed as linear low-density PE (LLDPE),

(b) *High Density Polyethylene (HDPE)* covers all types of PE with densities in excess of 0.940, and,

(c) *Linear Low Density Polyethylene (LLDPE)* is the third grade of PE.

Recent metallocene technology widened the range of properties and applications of polyolefins.

PE have very low compatibility with plasticisers and in fact it does not need plasticisers, however, they may contain other additives, (i.e., UV and heat stabilisers). Chloroparaffin or brominated flame retardant containing polyolefins should be used with caution.

PE (beginning from low-density PE (LDPE), medium-density PE (MDPE) and especially high-density PE (HDPE)) are mainly used for piping (mainly for pressure pipe production) and floor coverings in the construction industry. Plastic pipes provide a reduced number of joints, and in addition, PE pipes are preferred because of the inertness and mechanical properties of the material. However, HDPE has the greatest coefficient of thermal expansion (CTE) value of any plastic pipe material, almost three times that of PVC, which is one of its main drawbacks in construction applications. HDPE is commonly used in perimeter drain pipe around foundations, but rarely inside houses.

Porous PE nonwoven, breathable fabric is used as the strength component and starting material for both a perforated housewrap as well as several non-perforated breathable films in many other applications. These products are designed to offer the end user a range of products and performance up to the highest grade of breathable film housewrap.

Corrugated HDPE pipes are recommended for use in mortar, walls and concrete. Because the corrugated pipes are produced from pure HDPE they are resistant to stress cracking and therefore exhibit a flexibility that allows them to suffer slight denting without cracking or breaking.

Polyethylene foams (expanded polyethylene; EPS) have been known since 1941, and later developments in the production of different types of polyethylenes have made it possible to manufacture cellular products for their use in construction with better and better physical properties. HDPE and LDPE are often foamed with chemical crosslinking agents to reinforce the foam structure, converting thermoplastic material into a thermoset. The blowing agents usually used are different azobis-compounds which decompose at high temperatures to yield nitrogen and for crosslinking, different peroxides are used which yield products with a wide range of properties, i.e., LDPE foams can be semi-rigid or tough-rigid closed cell products. EPS foams are used in various applications for seals and insulation (on exterior walls, interior or between the walls, in flooring and hot water pipe insulations) in building and construction.

Polyolefin (PP and PE) floor coverings, power cables with PE coverings and HDPE pipes and wall covering materials, halogen free LLDPE and thermoset crosslinked polyethylene (XLPE) are all suggested as alternatives to PVC by Greenpeace, (PVC Fact Sheet. <www.healthybuilding.net>).

Additional information on polyolefins is provided in Chapter 2.

Poly(methylmethacrylate) (PMMA) and Acrylics

PMMA (or Plexiglas as it is commonly called) is a vinyl polymer, made by free radical vinyl polymerisation from the monomer methyl methacrylate. PMMA is a member of a family of polymers which are called either acrylates or acrylics. Acrylics are known for their excellent optical clarity, colour stability, and good weatherability characteristics and are used mostly for glazing, lighting, curtain-wall panels as a sealant and for decorative features.

PMMA is a clear plastic used as a shatterproof replacement for glass being more transparent and less dense than glass. The largest single window in the world, an observation window at California's Monterrey Bay Aquarium, USA, is made of one big piece of PMMA which is (16.6 m long, 5.5 m high, and 33 cm thick). PMMA is also found in paints: acrylic 'latex' paints often contain PMMA suspended in water. PMMA doesn't dissolve in water, so dispersing PMMA in water requires the use another polymer, poly(vinyl acetate) (PVAc) or it's copolymer, poly(vinyl alcohol-*co*-vinyl acetate) to make water and PMMA compatible with each other.

PMMA can contain some of its monomer, methyl methacrylate (MMA). MMA can also be evolved from thermal degradation of PMMA. Potential risks from the MMA mainly arise from repeated exposure to it. The absorption and hydrolysis of MMA to methacrylic acid and subsequent metabolism via physiological pathways results in a low systemic toxicity by any route of exposure. Health issues include asthma, dermatitis, eye irritation including possible corneal ulceration, headache and neurological signs. Exposures to very high levels of MMA (>1,000 ppm), which is normally highly improbable indoors under any condition, can result in neurochemical and behavioural changes, reduced body weight gain, and degenerative and necrotic changes in the liver, kidney, brain, spleen, and bone marrow. Relatively low concentrations can cause changes in liver enzyme activities. The data concerning MMA's ability to cause cardiovascular effects are inconsistent.

Additional information on PMMA is provided in Chapter 2.

Polystyrene (PS)

PS is a vinyl polymer and styrene is used as a monomer in the production of polystyrene plastics and resins. PS is mainly used in construction in the form of high performance expanded polystyrene foam (EPS), used for insulation for floors, walls and roofs.

Since PS progressively lose their deformation recovery properties with increase of plasticiser levels and yield to systems of little practical value, usually they are used 'neat', without

adding plasticisers. *Hence, the health hazard concern should be focused on the monomer, styrene, as discussed next.*

Acute (short-term) exposure to styrene in humans is known to result in mucous membrane and eye irritation, upper respiratory tract and gastrointestinal effects. Chronic (long-term) exposure to styrene results in effects on the central nervous system (CNS) such as headache, fatigue, weakness and depression, CSN dysfunction, hearing loss, and can cause minor effects on kidney function and blood as well. Human studies are inconclusive on the reproductive and developmental effects of styrene, hence the ECD effect of styrene is not established. Several epidemiologic studies suggest that there may be an association between styrene exposure and an increased risk of leukaemia and lymphoma. However, the evidence is inconclusive due to several confounding factors. The EPA's Office of Research and Development and the International Agency for Research on Cancer (IARC) concluded that styrene is appropriately classified in Group C, 'possible human carcinogen.'

Polystyrene foam, developed during 1930s (commonly known as Styropor - invented by BASF) uses either expandable bead moulding hydrocarbons incorporated during polymerisation (BASF process) and then the polymer beads are prefoamed by steam, or it involves use of chlorinated hydrocarbons during processing (Dow process) and physical foaming is activated by reaction heat. Both methods yield closed cell thermoplastic components that are mainly used for thermal insulation of buildings. For EPS, styrene monomer is used which is known to be toxic to the reproductive system, and hence the residual monomer poses a problem for use of EPS.

Without including expandable or modified grades, over 20 kT of PS was produced in Western Europe during 2003.

12.2.1.2 Some Thermoset Construction Materials (Polyesters, Epoxides, PU and Phenolics)

The industrial composites industry has been in place for over four decades. This large industry utilises various resin systems including polyester, epoxy, PU, phenolic and amino resins, bismaleimides (BMI, polyimides) and other specialty resins. Of these, epoxy resins are the most commonly used in today's construction industry. These materials, along with a catalyst or curing agent/hardener and some type of fibre reinforcement (typically glass fibres) are used in the production of a wide spectrum of industrial and structural components and consumer goods. When the mixture of resin, catalyst and reinforcement is cured, the finished part is produced. After this stage the part cannot be changed or reformed, except for finishing techniques which are applied afterwards.

Epoxy resins are used for durable and inert coatings, in laminates and composites and they are used as an adhesive. Since epoxies are relatively high molecular weight compounds and hence have low vapour pressures, the potential for respiratory exposure is very low, which is increased only when the resin mixture is applied by spraying or when curing temperatures are high enough to volatilise the resin mixture. Hence, epoxies do not pose any health hazard indoors. The potential for dermal (contact) exposure is, however, much greater than respiratory exposure. The basic epoxy molecule is a reaction product of epichlorohydrin (ECH) and BPA and some epoxies contain trace amounts of residual ECH (typically in the range of <1 to 10 ppm, by weight). However, industrial hygiene air monitoring has shown no detectable levels of ECH in the air and BPA exhibits toxic effects only at very high exposures and realistically, such high exposures are not possible indoors. BPA, as a chemical, is not a carcinogen or a reproductive or developmental toxin.

Curing agents are used with epoxy resins, the most commonly used ones are aromatic amines, and two of the most common are 4,4-methylene-dianiline (MDA) and 4,4-sulfonyl-dianiline (DDS). Like the epoxies, these compounds have very low vapour pressures and in principle they should not present any airborne hazard, unless a mixture is sprayed or cured at high temperatures and certainly potential for dermal exposure is high. Several other types of curing agents to consider are aliphatic and cycloaliphatic amines, polyaminoamides, amides, and anhydrides.

PU are compounds formed by reacting a polyol component with an isocyanate compound, typically toluene diisocyanate (TDI), diphenylmethylene diisocyanate (MDI) or hexamethylene diisocyanate (HDI). While the polyols are relatively innocuous, the highly toxic isocyanates can represent a significant respiratory (as well as a dermal) hazard. Exposure to the vapour may cause irritation of the eyes, respiratory tract and skin. Irritation may be severe enough to produce bronchitis and pulmonary oedema at high concentrations. PU resins with such impurities left may cause severe irritation to the eyes, and if such PU resin is allowed to remain in contact with the skin, they may produce redness, swelling, and blistering of the skin. Respiratory sensitisation (an allergic, asthmatic-type reaction) may also occur.

Catalysts used for PU foams are tertiary amines and organometallic compounds, particularly organotin compounds like dibutyltin esters. Tertiary amines are strongly basic and usually have high vapour pressures, causing irritation of skin or eyes as well as the respiratory system by its vapour. Although organotins are less irritant, contact should still be avoided. PU can be rigid (used mainly for insulation) or flexible (used for upholstery) and the former in the form of laminates are mostly being used in the construction industry.

Polyether polyol types used in PU foam production are found to be safe (they are low in oral toxicity with no irritation caused to the eyes and skin).

Phenolic and amino resins have well-known hazards due to both phenol and formaldehyde. In addition to traces of free formaldehyde, they may also contain free phenol. Free phenol is known to have a high skin-absorption potential.

The urea- and melamine-formaldehyde (UF and MF) resins present similar hazards. Free formaldehyde, which is present in trace amounts and may be liberated when their resins are processed or slowly afterwards, can irritate the mucous membranes (and can cause skin sensitisation). Formaldehyde is a metabolite occurring normally in the human body and is converted to formic acid by enzymic oxidation. Trace amounts of free formaldehyde can have an irritating effect on mucous membranes (and can cause skin sensitisation). Formaldehyde in the cured resin is believed to be due to left unreacted free formaldehyde, in addition, it is thought that it may be also be due to a demethylolation reaction and/or cleavage of methylene-ether bridges. UF resins and foams are banned in a number of countries.

The bismaleimides and polyamides are relative newcomers to the advanced composite industry and have not been studied to the extent of the other resins. However, it is reported that dust or vapour from heated products may cause irritation of the eyes, nose, and throat, which can hardly be the case indoors under normal conditions.

Comprehensive information about thermoset materials and their chemistry is presented in Section 5.2.

Low Density Plastics (Synthetic Foams, Cellular Plastics)

Low density plastics, with a range of densities between 2 kg/m^3 to over 1000 kg/m^3, generally consist of a minimum of two phases: a solid polymer matrix and a gaseous phase (hence that can be called solid-gas composites). It is known that physical properties of a foamed resin, change in direct proportion to the density of the material. Chemical properties of foamed and solid moulded parts are identical. Hence, data from the solid form may be extrapolated to provide foamed-part performance. Since densities of structural foams, which are affected by many factors, can generally vary from 45-100% below the base polymer, polymeric foams provide numerous advantageous properties. Foams can be 'flexible' or 'rigid' as well as 'semirigid' or 'semiflexible' [60]. The cell geometries may be open (generally flexible, softer and pliable, used in cushion foams and in acoustic insulation) or closed (generally rigid and hard, mostly suitable for thermal insulation because of its low thermal conductivity). Usually rigid foams with high densities and moduli are used for load-bearing applications and thermal insulation in construction, while low density flexible foams are mainly used for carpet backing and as cushions. Usually, rigid foams with densities greater than 320 kg/m^3 are termed 'structural foams' [40], which are increasingly used as substitutes for wood, metal or unfoamed plastics. During recent years, applications of plastic cellular

materials have mostly been in structural and in insulation areas (wall, ceiling and pipe). In insulation of both new and old buildings (retrofit insulation), fibreboard is the most used product for sheathing insulation, in addition to the use of extruded and moulded PS foam and foil-faced isocyanurate foam. In cavity wall insulation, mineral wool, PU, UF, and fibre glass are widely used. Especially in modular homes, cellular plastics are preferred because of their light weight and insulation capacity. PS and PU foams are used widely for pipe insulation. Cellular rubber and cellular PVC are preferred for small pipe insulation. Urethane-modified and glass fibre reinforced polyisocyanurate foam boards are widely used as insulation materials for buildings. Modified polyisocyanurate foams, with their light weights and high thermal insulations and strengths, are used on the outer walls of high rise buildings (curtain walls) and for insulation of metal siding (in Japan for the latter, for fire-proof outdoor walls). Extruded PS foam boardstock is used in residential sheathing and in roofing. Both PS and PU foams are preferred for roof insulations. A typical EPS is made of 98% air.

Within the problems that the foam industry faces, there are 'the residual chemicals left in the system' and 'flammability and smoke evolution on combustion'. Any unreacted monomer(s), blowing agent(s), polyols, catalyst(s) and/or fire retardants left and/or trapped in the system inside of the internal cells can be released slowly with time by themselves or as the cells are broken down by use, with the possibility of causing some health problems in both cases. The most widely used blowing agents are azodicarbonamide and azobisformamide, which give off the following gases during their reaction: ammonia, carbon monoxide and nitrogen.

Foams can contain residual monomers (styrene, vinyl acetate) and polyols as well as isocyanate (TDI and MDI) and hydrocarbon blowing agents. Organic isocyanates are strong respiratory irritants and can initiate asthma-like symptoms for overexposed persons and chemical sensitisation. Threshold limit values (TLV) for vapour exposure to cyanates are given as either 0.005 ppm (parts per million) as an 8 hour (for long-term exposure) ceiling limit or 0.02 ppm as a short-term exposure ceiling limit.

Foams, especially PU foams, present a considerable fire hazard. To supress flammability, certain additives (chemicals with elements such as phosphorus, halogens, antimony, nitrogen (melamine), and their synergistic combinations, called fire retarders or combustion modifiers), are added to the system. In addition to the foam itself, many flame retardants, i.e., halogen containing ones, contribute to smoke appreciably, and smoke evolution is shown to be a far greater danger to people than the fire itself. However, flame retarded rigid PU foams, when ignited at high temperatures, can give off cyanic acid (12 ppm) and a small amount of carbon monoxide [59]. The burning of polystyrene and PU (bulk or foam) releases a number of hazardous chemicals (styrene for the first, and isocyanates, hydrogen cyanide and may be even dioxin for the latter).

A model specification to set out the performance criteria and health hazards is presented for polymer mortar surfacings of epoxy, polyester and PU thermosets that are intended for use as indoor floor tappings [61].

In-depth information on foamed plastics is presented in Chapter 6.

12.2.2 Rubbers

Rubbers (or elastomers) are used mainly as floor coverings and membranes. Rubber flooring containing chlorine-based ingredients are not recommended because of the hazards involved. However, in most cases it is not true for other rubber types: ethylene propylene diene (EPDM) rubber is recommended by the Danish Environmental Protection Agency as an alternative to PVC.

The rubber industry uses hydrocarbon additives, specifically called process oils (which act more or less as plasticiser, used below 20 phr) or extenders (used to decrease the cost) to function as a plasticisers. There are a wide range of mineral oils used as process oils. They are produced by blending crude oil distillates and there are three main grades to consider: paraffinic (with branched and linear aliphatic hydrocarbons), naphthenic (with saturated ring structures) and aromatic. These, with compounds containing sulfur, nitrogen or oxygen are the polar component of the oil. The polycyclic aromatic hydrocarbon (PAH) containing process oils are classified as carcinogens, and their use is decreasing.

Liquid polybutenes are mainly used as process oils in EPDM formulations or where a product will have long-term weathering, i.e., for roofing membranes.

Emissions from building gaskets made from EPDM rubber indoors are tested in Sweden in an experimental wooden house at the Swedish National Testing Institute for exposure testing of rubber materials, at 20 °C [62].

The term plasticiser for rubber, usually refers to the synthetic liquids used with the polar rubbers, i.e., triethylene glycol di-2-ethylhexanote and similar esters are the most favourite low temperature plasticisers for polar synthetic rubbers.

Most rubbers burn easily. Self-extinguishing properties can be obtained by appropriate compounding. Burning rubber produces considerably high heat and acrid smoke which may contain harmful constituents, including halogens.

12.2.3 Wood and Wood Laminates

Wood by itself as well as its composite products, such as particleboard, plywood, and medium density fibreboard (MDF) are widely used in indoor products (structural panels,

subflooring, ceiling, door cores, as well as in cabinets, panelling and furniture). Particleboard and MDF are generic terms for a panel composed of cellulosic materials, generally in the form of discrete pieces or particles, and for a panel primarily composed of lignocellulosic fibres combined with a synthetic resin or other bonding system and bonded together under heat and pressure.

Most wood products are simple combinations of wood and water-based adhesives, the latter composed of mostly UF or PF, plus catalysts, filler and extenders (for plywood products). In some special applications, products can also be bonded with MDI. These resins mainly used as adhesives were blamed for causing a problem of emission of various toxic compounds. Interest on VOC emissions from wood products has so far focused mainly on formaldehyde, although formaldehyde is given in List 3 of Environmental Protection Agency (EPA) as 'a chemical of unknown toxicity' and phenol in the List 1 as 'chemical of toxicological concern'. The particleboard industry, primarily through new resin technology and better process control techniques, has reduced formaldehyde emissions to very low levels. Permissible limits of formaldehyde emission show differences from country to country (American National Standards Institute, ANSI, restricts this emission from particle board flooring to 0.2 ppm and for others to 0.3 ppm. OSHA has adopted a permissible exposure level of 0.75 ppm and an action level of 0.5 ppm, some states established a standard of 0.4 ppm. In their codes for residence others, i.e., California, established the lower level as 0.05 ppm; while in Germany, it is 6.5 mg/100 g and 7.0 mg/100 g of dry particle board and dry board for MFD, respectively, which corresponds to 0.1 ppm as also recommended by World Health Organisation (WHO). Melamine laminates that are commonly used for kitchen and bathroom cabinets, door facings and countertops may have residual formaldehyde volatiles also from either the laminate itself or the substrate material.

Formaldehyde is normally present in air, at low levels (<0.03 ppm). Typical levels of it found in the smoking section of a restaurant are approximately 0.16 ppm.

Tests with composite wood products have also yielded certain volatiles of different preservatives, in addition to formaldehyde. These can be different volatile solvents or free monomers and plasticisers or from coatings applied to them, as well as from the adhesives. The latter are commonly phenol- or formaldehyde-based and they are used in the manufacture of compressed fibre, composite board and plywood materials. As far as the coatings are concerned, some products that are sealed with a polymeric film or coating that can trap residual volatiles and allow a slow gradual release of VOC over a period of time). The binding agents used in particle board and plywood can contain volatile phenols and traces of residual solvents.

In the laminate application of wood (particularly on cabinets and cupboards that are made from porous composite wood materials such as particle board), it is always possible to

have trapped solvents (mainly aromatic hydrocarbons like toluene and xylene and ketones like acetone and methylethyl ketone) in the adhesives. The adhesive solvents that are absorbed at the wood surface can diffuse into the air, over longer periods of time, and in small amounts. Xylene and toluene are given in the List 2 of EPA as 'potentially toxic'.

Formaldehyde is a strong irritant to mucous membranes. Adverse health effects that are associated with increased VOC concentrations of formaldehyde can begin with eye and respiratory irritation (including allergy and asthma), irritability, inability to concentrate and sleeplessness, and can end up with more serious health problems. The EPA tested formaldehyde levels in a newly constructed test home that contained various UF-bonded building materials and found values below that expected (0.06 ppm), and it is not clear whether adsorption of formaldehyde, most notably by painted gypsum wallboard, contributed to this unexpected result or not [63].

In addition to the improvements involved in resin technology and better process control techniques, there are different methods applicable to produce wood products with lower - even with minute - formaldehyde emissions as well. Within these, there are several approaches to consider:

- resin formulation can be changed
- ageing can be applied to it - emissions decay considerably with time such that within a year or so, their level can be as low as the background,
- formaldehyde scavengers, such as urea solution can be used – which is mainly applied in the USA
- by application of proper coating/laminates - formaldehyde emissions can be reduced by as much as 95% with a sealing finish, or
- the process can shift completely to the melamine-urea-formaldehyde (MUF) process – this technique is mainly applied in Europe.

Recently, there has also been a growing interest in the production of wood and wood products without any other possible non-formaldehyde VOC emissions. Recent results showed the existence of other volatiles, mainly terpenes, ketones, acetone and hexanal, in addition to aldehydes in such systems [39, 64, 65].

Wood furniture coatings usually contain urethane/isocyanates in addition to UF, volatile plasticisers, residual solvents and free monomers from incomplete polymerisation of the coating. Nitrocellulose lacquer, acrylic, cellulose acetate butyrate and polyurethane (with plasticisers like epoxy, di-butyl phthalate, butyl benzyl phthalate and isopropyl myristate) are the coatings commonly used on clear finished wood furniture. In these, the amounts and

the types of VOC mainly depend on the type of curing. Heat cured and high solid coatings usually retain the lowest amounts of organic solvents. In one study, emission characteristics of the release of VOC, especially detection of photoinitiator fragments, from UV cured furniture coatings was studied, and it was found that they contribute significantly (20-60%) to the total emission [66]. One main compound found in this study was benzaldehyde, generated by many applied photoinitiators via cleavage. While in another similar study [67], environmental issues indoors related mainly to wood products and furnishings were surveyed.

Since the 1940s, lumber producers and manufacturers have used a chemical compound mixture that contains inorganic arsenic, copper, and chromium called chromated copper arsenate (CCA) as a wood preservative. CCA is usually injected into wood by a high pressure process to saturate wood products with the chemicals, to produce 'pressure-treated lumber', (between 75 and 90% of the arsenic used in the United States is estimated to be used for wood preservation).For more information on wood and wood-plastic composites used in construction, see Chapter 9.

12.2.4 Other Hazardous Construction Materials and Possible Health Hazards From Some Construction Applications

12.2.4.1 Asbestos

Before the mid-1980s, one of the main ingredients used in the resilient flooring and acoustic ceiling tiles industry was asbestos. Asbestos is a mineral and is hazardous to health when it becomes 'friable' or 'free floating and airborne', as in dust. Asbestos was outlawed a long time ago, it is no longer used in construction. But in an old building prior to the mid-1980s, it can still be found as an insulating coating on steelwork or concrete, as lagging on pipes and boilers, as insulation boards in walls, on doors and ceilings or as asbestos cement for roof and wall coverings, pipes and tanks, and in some decorative plasters. The danger comes from drilling, cutting, sanding or disturbing materials made from asbestos and by breathing the dust. The EPA has determined that encapsulated or nonfriable asbestos containing products are not subject to extensive regulatory requirements as long as they remain in that state, provided that they are not sanded, sawed or reduced to a powder. There are still a number of people that suffer each year from asbestos-related diseases, mainly cancer [68-70].

12.2.4.2 Sealants

As discussed briefly in Section 12.1.7.1.2, PCB, a family of highly toxic and oily non flammable industrial chemicals, can exist at high levels in and around some old buildings, due to sealants

based on polysulfide polymers containing PCB being used. PCB in many polysulfide sealants have been replaced now by chlorinated paraffins and smaller volumes of chloroparaffins are used as plasticising agents for various sealants. However, the effects of chloroparaffins on health is also a controversial issue and its use in sealants is in decline. In sealants, especially in polysulfide and PU sealants: butyl benzyl phthalate (BBP) is also used [71].

Polyurea seals are 100% solid, with high elongation and self-levelling elastomers. They are VOC free, used in horizontal saw or preformed joints on concrete or asphalt.

12.2.4.3 Paints, Varnishes and Lacquers

Paints, varnishes and lacquers contain various solvents as carriers. When a paint is applied in liquid form, a volatile component (mineral spirits and white spirits for alkyds, water for latex emulsions, alcohol for shellac and lacquer thinner for lacquers, in addition to xylene, naphtha, etc., used as thinner) evaporates and the non-volatile portion of the paint (binders: liquid adhesives that form the surface film) is left on the surface. Binders can be natural (shellac, rosin, lindseed oil) or synthetic (alkyd, epoxy, urethane or styrene butadiene in water-based paints as well as acrylic/vinyl acrylic latexes, latex referring to water-based). To comply with the VOC emission laws, more solids are added which eventually makes the paint thicker and take longer to dry. Depending on the drying speed, application and the type of finish that results, variations in the type of solvent is possible. The most common solvents encountered in construction are: white spirit, xylene and 1-butanol. Some paints, long after their curing and drying, can still give off some residual odours, which can be due to a number of factors, (i.e., due to un-reacted monomers used in the manufacture of the resins and plasticisers or trapped solvents in small amounts).

In the case of water-based or latex emulsion type paints, there would be un-reacted (free to evaporate) monomers, glycols and glycol ethers, alcohols, amines, and possibly formaldehyde, free monomers and plasticisers, that will continue to be generated for a long time after the paint has dried. However, the VOC level in a water-based paint is generally much lower than other common solvent-based products due to slower evaporation of VOC producing constituents.

Glycols, such as ethylene and propylene glycol are commonly used in interior and exterior latex/emulsion based coatings with concentrations of 2 to 5% by weight. They evaporate very slowly. The glycol ethers are needed for proper film formation, they evaporate slowly and can remain in the applied coating film for a period of about 72 hours or longer. Preservatives used in water-based paints were a mercury compound such as phenyl mercuric acetate or formaldehyde, and they are substituted by other organic preservatives now. Amines can be of different types: from fast evaporating (ammonium hydroxide) to

slow evaporating (amino-2-methyl propanol). The types of free monomers in water-based/latex paints depend on the type of polymer or its blend used, and are the basic building blocks of the adhesive film forming polymer.

Petroleum solvent-based paints contain aliphatic and aromatic hydrocarbons, ketoximes, alcohols, free monomers and plasticisers. In a general purpose petroleum solvent-based paint the volatile components are aliphatic hydrocarbons and paraffin naphtha. Odourless solvents (isoparaffinic naphtha or petroleum distillate) used in some interior oil/alkyd-based coatings can pose a danger for hypersensitive persons.

Fast drying paints generally contain certain aromatic hydrocarbons (toluene and butyl acetate) and smaller volumes of chloroparaffins are used as plasticising agents for various paints, however, the effects of chloroparaffins on health is still a controversial issue and its use in paint applications are in decline.

Varnish is a transparent (or pigmentless) film applied (to stained or unstained wood) and contains volatile solvents like white spirits and 1-butanol.

12.2.4.4 Adhesives, Polishes and other Maintenance Materials

Solvent-based adhesives (commonly used on laminates, tiles, parquet and vinyl flooring) can contain alcohols, ketones, hydrocarbons, plasticisers, and some monomers [71].

Water-based adhesives can contain formaldehyde (as preservative), amines, glycol ethers, alcohols, plasticisers (and some free monomer depending on the type of polymer and polymerisation used). Smaller volumes of chloroparaffins are used as plasticising agents for various adhesives.

With both types of adhesives, a long-term, slow release of the VOC are expected due to their possible absorption into the surface and hence sealing of the adhesive.

Adhesives used in carpet backings can contain residual formaldehyde or isocyanates and vinyl acetate and various hydrocarbon solvents (from treatments and adhesives used to laminate the backing). From new carpeting, 4-phenylcyclohexane (4-PC, a by-product of styrene-butadiene commonly used to bind the backing) is usually emitted which is claimed to cause headaches, sore throats, lethargy, skin and eye irritation even at very low concentrations (1 part per billion). Chlorinated paraffins (mainly CPVC) is widely used in PVC for adhesive applications, mainly to gain greater resistance to ignition and combustion than general purpose plasticisers. However, the effects of chloroparaffins on health is still a controversial issue and its use is decreasing [41].

Cleaners, waxes and polish can contain a number of chemicals, along with a volatile carrier.

12.2.4.5 Wall-Coverings

Although the terms wall coverings and wallpapers are used interchangeably, they may be made of paper backed by cotton fabric, vinyl face with paper or cotton backing, fabric with a paper backing or may be all paper. Wall coverings are mainly one of the flexible PVC applications (in vinyl coated paper, paper backed vinyl/solid sheet vinyl, fabric backed vinyl, etc.), and they may contain some free monomers, (i.e., vinyl acetate, styrene, acrylic and even vinyl chloride), plasticisers (general purpose, mostly phthalates, like DOP, DINP or DIDP are used), adhesives and certain preservatives. Adhesives used for wall-coverings in general are modified starch products and special adhesives can be either styrene-butadiene or vinylacetate-ethylene copolymers with organic solvents and preservatives.

Chlorinated paraffins (mainly CPVC) are widely used in PVC for wall paper applications, to introduce greater resistance to ignition and combustion than general purpose plasticisers. However, the effects of chloroparaffins on health is still a controversial issue and its use as a flame retardant is decreasing [41].

12.2.4.6 Wires and Cables

Cable application of plastics is mainly done with PVC in the form of PVC-P, because of the economy and fire safety provided by the base polymer PVC. Chlorinated paraffins (mainly CPVC) are widely used in PVC to give greater resistance to ignition and combustion than general purpose plasticisers where CPVC are large sized molecules with almost no probability of emission. However, the effects of chloroparaffins on health is still a controversial issue and its use as a flame retarder in PVC applications for cables are decreasing [41]. The most common plasticisers used in cables in Europe are DOP and DIDP. In high temperature PVC cable applications, trimellitate plasticisers (preferably high molecular weight versions) are mainly used, without any health hazard expected.

12.2.4.7 Piping and Fittings

Plastic pipe and fittings, particularly PVC-P and to some extent PE, are overwhelmingly being used in construction as a big competitor of metallics. Rapra's report [72] demonstrates that plastics' use in gas, sewage and water piping has tripled in the EU. Health hazards in such PVC-P pipes and fittings, are subject to emission of the plasticisers used.

12.2.4.8 Flooring and Floor Tiles

'Safe kids', a non-governmental organisation, with headquarters in Washington, DC, USA, selected a playground material made from PVC, because they are found to be 'safe,

non toxic' and 'ideal in preventing the accumulation of allergic bodies such as fungi and mildew'. In fact, PVC floors are commonly used in 'many nursing homes and hospitals, in particular in operating theatres'. Since flexible PVC is needed in such flooring, it is necessary to use plasticised PVC. Usually general purpose plasticisers (various phthalates, DOP, DINP and DIDP) are used for this purpose. RAPRA's report [72] demonstrates that plastics' use in floor coverings in construction rose from 160 000 tonnes in 1970 to 343 000 tonnes during the period of 1970 to 1995.

Chlorinated paraffins (mainly CPVC) are widely used in PVC to have greater resistance to ignition and combustion than general purpose plasticisers. Hovewer, the effects of chloroparaffins on health is still a controversial issue and its use as flame retarders in PVC applications for flooring are decreasing [41]. For cushion vinyl flooring applications, several phthalates such as DOP are used due to its cost and the safety provided, BBP or di-isoheptyl phthalate as well as plastisols of PVC plasticised with 2,2,4-trimethylpentan-1,3-diol di-isobutyrate are also used.

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13 Glossary

Güneri Akovali

A

Ablative
Material that absorbs heat through pyrolysis at or near the exposed surface.

Accelerator
An active material that is suspended in a liquid carrier to produce heat to accelerate the cure of a liquid resin. Accelerators usually work in conjuction with an initiator.

Acetal resin
Linear, hard, tough synthetic resins produced by the polymerisation of formaldehyde (for acetal homopolymers) or of formaldehyde with trioxane (for acetal copolymers). Acetal resins are also called as polyacetals and are used as substitutes for metals.

Activator (see Accelerator)

Active envelope
Consists of two panes with a cavity in between, through which air flows. They are also known as double-skin facades, twin facades or second-skin facades. (See also Building envelope)

Adhesive
A liquid, film or paste applied to the mating surfaces to bond them together by surface attachment. They are substances capable of holding two or more surfaces together in a strong, often permanent bond, which may provide a specific function in themselves as well.

Addition polymer/(polymerisation)
Long chain molecules (polymers) formed (the chemical reaction to form polymers) between one or more different types of monomer units with unsaturation (double bonds).

Additives
A large number of different chemicals that are added to polymers to impart specific properties, such as flame retardancy and UV resistance.

Additive toxic effect
Where materials with similar toxicities produce a response equal to the sum of the effects produced by an individual material.

Aerogel
One of the strongest, lightest and yet transparent (although non-polymeric) building products with 99% empty volume, typically produced from silicone or carbon.

Antagonistic toxic effect
Where materials oppose or interfere with each other's toxicity.

Antiblock agent
An additive incorporated in polymer film to prevent the sticking of the touching layers during fabrication, storage or use.

Antioxidant
An additive which inhibits the degradation and oxidation of a polymeric material when exposed to ambient air during processing and in the end product.

Antistatic agent
An additive which permits the dissipation of static electricity in plastics through imparting a slight degree of electrical conductivity.

Admixtures for concrete
Materials other than cement, water, aggregates and fibres, used as concrete ingredients which are added to the concrete batch before or during mixing.

Air barrier
Products that keep infiltration of exterior unconditioned air from entering the building.

Alkyd resin
A group of synthetic adhesive resins produced from unsaturated acids and glycerol. Unsaturated polyester (uPES) resins based on phthalic anhydride obtained in the early 1930s. They are also called glyptal resins.

Allyl resin
Thermosetting synthetic resins produced from esters of allyl alcohol or allyl chloride, also called an allyl plastic.

Amino resin
Synthetic condensation product of aldehyde and a compound containing an amino group.

Antioxidants
Chemicals that help prevent the polymer from reacting with oxygen.

Antistatic agents
Chemicals that help to prevent the build up of static electric charge.

Aramid fibre (AF)
A high-strength, high-stiffness, aromatic polyamide fibre.

Aspect ratio
Length-to-diameter ratio (L/D) in fibres.

Asbestos
A natural inorganic fibrous material, mainly composed of chrysolite, that was used as an effective reinforcing material in the past. Asbestos is a proven lung cancer producing agent and its use is banned.

ASSET (Applications of Smart Structures in Engineering and Technology) www.mouchel.com
European Brite-Euram research project and EU Thematic Network to develop lightweight, durable decking systems and smart structures for buildings using advanced composite materials.

Atactic (polymer)
A type of polymer molecule where substituent groups or atoms are arranged randomly above and below the backbone chain of atoms, when the latter are all in the same plane.

B

Ballast
Granular material supporting railway tracks.

Beam
A structural member with a bigger length than its depth or width that resists loads perpendicular to its longitudinal axis. (See also composite beam)

Binder
Solid ingredients in a coating (that hold pigment particles in suspension and attach them to the substrate), which consist of resins (oils, alkyd, latex), the nature and amount of which determines the paint's performance such as its washability, toughness, adhesion, colour retention, etc.

Blister/blistering
Raised undesirable areas in a plastic moulded part (or on the surfaces of walls in houses). Blisters can be produced by trapped air, as well as by volatile by-products or water.

Blowing agent
A substance which, alone or with others, has the capacity to produce a cellular structure in a plastic mass.

Branched polymer
A polymer in which side chains are attached to the backbone of the molecular chain.

Branching
Lateral extension of a main chain in a polymer chain.

Building
Any structure built with walls and a roof, used, or intended to be used, for shelter.

Building envelope
All building components that separate the indoor from the outdoors which provides a thermal shell.

Building related illness (BRI)
A variety of illnesses that have been attributed to toxic fumes inside a building.

Bulk moulding compound (BMC)
Uncured thermoset resin/glass fibre premix for injection or transfer moulding, also known as dough moulding compound (DMC). (See also DMC: Dough moulding compound)

C

Carbon fibre (CF)
Fibre which is produced by high temperature treatment of an organic precursor fibre based on polyacrylonitrile (PAN), rayon or pitch in an inert atmosphere at temperatures above 1000 °C. It is a reinforcing fibre known for its light weight, high strength and stiffness.

Casa Forte
Brand name of Medabil (Brazil) patented all-vinyl houses and the first group of plastics condomium vinyl houses (Casa Forte meaning strong house).

Catalyst
A substance (usually a peroxide) which initiates and accelerates the polymerisation reactions without being consumed itself. It is also known as a hardener. (See Initiator and Hardener)

Cavity
In processing: the space between matched moulds, also the female mould half.
In walls: the space between the bricks.

Celluloid
The first plastic material obtained by chemical modification (nitration) of cellulose.
Also known as cellulose nitrate.

Cellular polymers (or cellular plastics/polymer foam)
Multi-phase material systems (composites) that consist of a polymer matrix and a fluid phase, the latter usually being a gas.

Cellulosic resin
Any resin based on cellulose compounds such as esters and ethers.

Chain length
The number of monomeric or structural units in a linear polymer.

Chain extenders
Substances which lengthen the main chain of a polymer molecule with end-to-end attachments.

Chopped strand/(chopped strand mat)
Cut continuous strands into shorter (approximately 50 mm) lengths not held together by any means/(chopped randomly oriented strands held together through by size (thin gelatinous mixture amde from glue, wax or clay)).

Chlorinated paraffins
Effective flame retardant additives for polyester resins.

Chlorosulfonated polyethylene
This material, also called Hypalon, shows its strength when exposed to high temperatures and oxidising chemicals; it has excellent resistance to ozone and weathering. This accounts for its success in roofing, belting, and wire and cable.

Chromogenic
Property that functions as optical switch. (See also electrochromic, photochromic, thermochromic and thermotropic).

Coating
A polymer film used to cover, protect, decorate or finish.

Co-extrusion
The technique of extruding two or more materials through a single die while being fed by separate extruders.

Co-polymer
An addition polymer of at least two chemically different monomers.

Condensation resin
Any resin produced by a polycondensation reaction of at least two monomer units containing functional units, during which, a by-product of low molecuular weight is also usually produced.

Compatibilisers
Chemicals that help to blend different types of waste plastics and ingredients.

Conduction heat
Heat energy transferred directly through materials in contact with each other where a temperature difference exists, i.e., conduction of heat along a metal rod.

Convection heat
Air movements occurring in spaces between the framing members of ceilings or walls of a building.

Coating
A polymer film used as cover, protection, decoration or finish. It is applied to a substrate surface and which becomes a continuous film after drying.

Coefficient of thermal expansion (CTE)
A material's fractional change in length for a given unit change of temperature.

Composite (polymer)
A material made up of a polymer matrix and reinforcement.

Composite beam
A structural member with two or more dissimilar materials all joined together to act as a unit.

Compression strength
The crushing load at failure divided by the cross-sectional area.

Condensation polymer/(polymerisation)
Long chain molecules (polymer) formed /(the chemical reaction to form polymers) between two or more monomer units with functional groups, in most cases, with the production of a by-product.

Configuration
The stereochemical arrangement of an atom's configuration which cannot be altered without breaking the chemical bonds.

Conformation
The geometric arrangement of atoms in the polymer chain which can be altered by rotation of atoms.

Consolidation
Compression of soil due to expulsion of water from the pores.

Contact moulding
Moulding of fibre-reinforced resins without application of external pressure.

Copolymer
A polymer produced from at least two different monomers, or a polymer with more than one different type of monomer unit.

Core
The central foam or honeycomb component in sandwich construction, to which inner and outer skins are attached.

Corrosion resistance
The ability of a polymeric material to withstand contact with ambient weather or severe special chemical conditions, without degradation or any appreciable change in properties. Environmental corrosion can usually cause crazing of polymer composites.

Coupling agent
A chemical that promotes (or establishes directly) a stronger bond at the polymer matrix and reinforcement interface.

Crazing
Fine cracks on or under the surface.

Critical (fibre) length
Minimum length of a fibre required for the fibre stress to develop its maximum value when a composite is under load.

Crosslinks(X-links)/(crosslinking)
Chemical links/(the setting up of chemical links) between different molecular chains. A high amount of crosslinking can convert a thermoplastic into a thermoset, and this can be accomplished by chemical reaction, vulcanisation, degradation and radiation.

Crystallinity
The state of a molecular structure denoting uniformity and compactness of the polymer chain.

Cure
The crosslinking/total polymerisation of the molecules via transformation of liquid resin into a hard solid state under the influence of heat. Cure refers to the completeness of the chemical reaction processes.

Cure time
Time required to cure the system completely after initiators are added.

Curing agents(also known as hardeners)
Chemicals used to cure thermosetting polymers (to bring the system chemically from a liquid, paste or mortar consistency to a solid plastic).

D

Degradation
A change in the chemical structure, physical properties or appearance of a plastic caused by exposure to heat, light, oxygen, other irradiation or weathering.

Degree of polymerisation (average)
Number of repeating units in the chain. It is used as a measure of the length of polymer chains.

Delamination
Splitting, physical separation or loss of bond of ply layers due to adhesive failure in a laminated material.

Dimensional Stability
Ability to retain a given shape and size.

Di-isocyanate
A reactive chemical grouping of a nitrogen atom bonded to a carbon atom bonded to an oxygen atom: -N = C = O. A chemical compound, usually organic, containing one or more isocyanate groups.

Discoloration
Any change from the initial color of a plastic.

Dose-response assessment
The determination of the relationship between the magnitude of exposure and the magnitude and/or frequency of an effect.

Dough moulding compound (DMC)
Polyester/resin fibre premix, for injection or transfer moulding. It is also called bulk moulding compound (BMC).

Drainage
Removal of excess surface or ground water.

Dry film thickness (DFT)
The mil thickness when the coating has dried.

Durability of concrete
Ability of concrete to resist external and internal aggressive effects.

E

E-glass (electrical glass)
Borosilicate glass fibres (which are most often used in conventional polymer matrix composites).

Elastomer
A synthetic rubber-like, material capable of rapid, reversible extension.

Electrochromic
A property where a small electrical current is used to alter the transmission properties. (See also photochromic, chromogenic, thermochromic and thermotropic)

Epoxy resin
A polyester thermoset material prepared by polymerisation of bisphenol and epichlorohydrin, with high strength and low shrinkage during curing, used as a bonding matrix to hold fibres together or used as a coat, adhesive or foam.

Exotherm curve
Temperature *versus* time chart of a resin mix during curing where peak isotherm is the maximum temperature of interest.

Exotherm heat
Heat given off during polymerisation reaction/curing of the resin.

Extenders
Ingredients added to paint (a) to increase coverage, (b) to reduce cost, (c) to achieve durability and (d) to alter the appearance. Extenders are less expensive than prime hiding pigments, i.e., titanium dioxide.

F

Fabric
Woven material, older term for geotextile.

Fibre
A material of relatively short length with a high ratio of length to thickness or diameter with the ratio of minimum length to maximum transverse dimension of 10:1.

Fibre, continuous
Fibres with aspect ratios much bigger than 5000.

Fibre, discontinuous
Fibres with aspect ratios between 100-5000 (See also filament, yarn, strand/chopped strand).

Fibre content
The amount of fibre in a composite expressed as a volumetric ratio.

Fibre reinforced concrete
Concrete containing fibres as reinforcement.

Fibre reinforced polymer (FRP)
A composite material or part that consists of a resin matrix containing reinforcing fibres having higher strength or stiffness than the resin.

Fibrillated yarn
Yarn split into thin fibres.

Filament
Individual single strand of natural synthetic fibre of small diameter (up to 0.0025 mm in diameter) with indefinite continuous length.

Filler (inert)
An inorganic, low cost, inert material added to polymers to improve properties, and to extend volume to reduce costs. Fillers are usually solid, particulate materials.

Filtration
Unimpeded flow of water through granular filter or geotextile layer without significant washout of fines (small particles) from natural soil.

Fittings
A word used for the tap assembly, used by the plumbing industry.

Finishing
Application of coupling agent(s) to textile reinforcements to improve the interfaces and the fibre/resin bond.

Flame retardant
Chemicals that help to prevent (a) the ignition or (b) reduce the spread of flame in a plastic material when exposed to high temperature, and/or (c) insulate the substrate and delay damage to the substrate.

Flammability
The measure of the extent to which a material will support combustion.

Flash
A thin, surplus of material that remains attached to the moulded plastic article, which is removed by deflashing operations.

Flexural strength
The strength of a material in bending.

Flow
The movement of thermosetting or thermoplastic material under pressure to fill all parts of a closed mould.

Formica
Trademark for laminated sheets produced from melamine/phenolic plastics. (The term mica- describing the use of hydrous disilicates as insulation for electrical applicances).

Free radical
An atom (or group of atoms) with at least one unpaired electron.

Functionality
The number of reactive groups in a chemical molecule.

G

Galalith
(from the Greek: gala = milk, lithos = stone) known as milk stone, is a modified natural polymer produced by reacting casein, a milk protein, with formaldehyde.

Gabion
A box made of wire mesh or geogrid filled with stone.

Gate
The opening in the mould through which melted compound is injected into a closed mould, the size and geometry of which can affect properties of the finished product.

Gel
A partially cured resin with a semi-solid jelly consistency.

Gel coat
Protective thin surface coating on the outer surface of a reinforced mould used to hide the fibre pattern of the reinforcement, protect the system and to give smooth external finish.

Gel time
Time required to change a liquid resin to a non flowable gel.

Geocell
Interlocking cells of geogrid filled with granular soil, forming a mattress to provide stability. A row of geogrid cells is typically 1 m high, filled with sand or gravel.

Geocomposite
Manufactured material using a combination of geosynthetics.

Geofoam
Polymeric foam used for insulation, infill and vibration damping.

Geogrid
A planar, grid-like polymeric material with large apertures used mainly to reinforce soil and asphalt pavements.

Geomembrane
A practically impervious polymeric sheet used as a liquid or vapour barrier.

Geonet
A planar, polymeric material which resembles a net and is used primarily for liquid and vapour transmission.

Geopipe
Plastic pipe placed beneath the ground surface and subsequently backfilled.

Geosynthetic(s)
Common name for all kinds of synthetic materials including geotextiles, geomembranes, geonets, geogrids, and so forth, used in geotechnical and civil engineering applications.

Geotechnical engineering
A branch of civil engineering that deals with the analysis of soil behaviour, design of foundations and earth structures.

Geotextile
A planar, polymeric, permeable textile (geosynthetic) used for geotechnical engineering purposes.

Glass fibre (GF)
Reinforcing fibre made by attenuating molten glass known for its good strength, processability and economy, generally spun from the molten standard E-glass to approximately 9 μm in

thickness. These fibres are bundled together on a drum and can then be used as continuous rovings, and used generally either as chopped strand (20-50 mm) or as woven mat.

Glass transition temperature (T_g)
Temperature at which a reversible change in an amorphous polymer between a viscous, rubbery condition and a hard and brittle one takes place.

Glaze
A glossy coating, also known as enamel.

Glazing
(a) Cutting and fitting of panes of glass into frames, or
(b) The application of ground glass or glass-forming materials to a ceramic surface by melting.

Granular filter
Layer of granular soil of selected gradation used for filtration.

Glyptal resin
Unsaturated polyester resins based on phthalic anhydride obtained in the early 1930s. They are also called alkyd resins.

H

Halocarbon resin
Resin produced by the polymerisation of halogenated hydrocarbon monomers, like tetrafluoroethylene (C_2F_4), and trifluorochloroethylene (C_2F_3Cl).

Hardener (see Initiator)

Hazardous material
Any material or substance which can be damaging to the health and well-being of man (such as poisons/toxic agents, corrosive chemicals, flammable materials, explosives, radioactive materials).

Heat stabilisers
Chemicals that help to prevent decomposition of the polymer during processing.

Heat transfer coefficient (U, with units of W/m^2K)
Quantity of heat flowing through a 1 m^2 area during one hour when there is a difference in the hot and cold side temperature of 1 K. It is also called the 'heat loss factor'. (In the French and German technical literature, it is known as 'Coefficient k' or 'k-wert', respectively).

High-range water reducing admixtures (HRWRA)
Admixtures that reduce the mixing water requirement of a fresh concrete with a given consistency by more than 12%.

Homopolymer
Polymer produced from a single type of monomer.

Honeycomb
Light weight, cellular structure formed into hexagonal nested cells, similar in appearance to the cross-section of a beehive.

Hybrid
A resin or reinforcement made from two or more different polymers or reinforcement materials.

Hydroxyl
An alcoholic group (-OH). (See also the reactive group in polyols).

Hypalon (CSPE)
Chlorosulfonated polyethylene.

Hydrolysis
Decomposition of a substance by reaction with water.

I

Impregnate
To saturate the voids and interstices of a reinforcement with resin.

Impact modifiers
Chemicals that enable plastic products to absorb shocks without cracking.

Indoor air quality (IAQ)
The result of measuring the air inside a building for toxic emissions.

Infiltration (i)
Loss or gain of heat through areas where inside and outside air meets, through leaks.

Inhibitor
Chemical that retards polymerisation and increases gel time.

Initiator
Chemical which produces free radicals, also known as a catalyst.

Inorganic polymers
A group of polymers that do not contain carbon atoms but all of the elements of group IV with linear chains analogous to those of polyethylene. Inorganic polymers are also called mineral polymers.

Insulation strength
The ability of a particular thickness of a material to resist heat flow (rated in terms of R, the thermal resistance, in m^2K/W).

Intumescence/(intumescent)
A property of a material which swells when heated/(a material able to swell during heating, forming an insulating protective layer over the substrate). Intumescent materials are used as fireproofing agents.

Isocyanate resin
A linear alkyd resin with excellent abrasion resistance, chains of which are extended by isocyanates and glycol or diamine and then crosslinked.

Isotactic (polymer)
A type of polymer structure where groups of atoms that are not a part of the backbone structure are located either all above or all below the atoms in the backbone chain, when the latter are in one plane.

L

Laminates (laminar composites)
A composite where the reinforcing phases are in the form of sheets bonded together and are often impregnated with more than one continuous phase in the system.

Landfill
A waste disposal site for the deposit of waste onto or into land, i.e., underground.

Latex
The suspension of a water insoluble substance, like polymethylmethacrylate (PMMA), held in suspension by being wrapped in another kind of molecule in paints. (See also latex paints)

Latex paint
A paint that is composed of latex(es). (See also latex)

Latex-modified concrete (LMC)
Portland cement concrete produced by replacing a specified portion of the mixing water with a latex (polymer emulsion).

Lay-up
A resin impregnated reinforcement in the mould, prior to polymerisation.

Leachate
Contaminated liquid formed by the passage of water through waste.

Linoleum
A product (from the Greek: linum = flax, oleum = oil) composed of a coarse fibre backing coated with a mixture of linseed oil, cork filler, rosin, binders plus the desired colorants.

Lubricants
Chemicals that help to prevent damage to plastics or the mould during processing.

M

Macrocomposite
A composite where there is more than one continuous phase present.

Masonry
A widely used construction technique and one of the oldest family of building material. Common masonry materials being stone, brick and concrete masonry.

Mat
Sheet type reinforcement made up of filaments, staple fibres or strands that are lightly bonded together (in cut or uncut, oriented or random shapes).

Median lethal dose (MLD or 'LD 50')
The dose (in mg/kg body weight) killing 50% of a sample population from statistically treated dose-response data. It is a measure of the strength or potency of poisons.

Microcomposite
A composite where all the dispersed phases are between 10-1000 nm in size and with only one continuous phase.

Micron (μm)
A unit of length equal to 0.001 mm.

Migration
The exudation of an ingredient from one material to an another, i.e., migration of plasticiser from one plastic material into an adjacent one with a lower plasticiser content.

Mildew
Discoloration caused by fungi.

Mil
Measurement of thickness of film, which is equal to 25.4 mm.

Mineral Polymer
Inorganic polymer.

Modbit
A polymer modified bitumen.

Monomer
A low molecular weight starting material (either with double bond or functional groups) to produce polymers.

Mould
Enclosure, usually metal, in which a plastic material takes its final shape.

Mould Release
Chemical or chemicals used to coat the mould to prevent the product sticking to it.

N

Nanotechnology
Is the design, fabrication, and characterisation of functional objects having dimensions at the nanometer (one billionth of a metre) length scale.

Nanocomposite
A microcomposite where sizes of reinforcing components are in the form of 'quantum dots' specifically smaller than 25 nm.

Nonbridging
A paint that will not cover the small holes in an acoustical tiled ceiling.

Non-Structural Elements
Non-load bearing structures (like sidings, window frames, piping, wall papers, etc.), in housing construction.

Nonwoven Fabric
Fabric produced from fibres or yarns without interlacing, e.g., stitched.

Novolac resin
An additive used in varnishes. A thermoplastic phenol-formaldehyde product, produced with excess of phenol in the mixture.

Nylon
A member of the family of polyamides.

O

Off-gassing (see also out-gassing)
The process by which toxic fumes are emitted from a substance, i.e., carpet when it is newly laid.

Organic polymer
Polymer group that consists of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), halogen atoms, or O, N, or S in some cases, on the backbone chain.

Orthophthalic resin
An unsaturated polyester resin originated from phthalic anhydride.

Out-gassing (see also off-gassing)
The release of volatile organic compounds from building materials, furniture and synthetic composites, which usually increases with increase in temperature.

Overlay
A layer of asphalt material placed on top of an existing pavement for purposes of repair and strengthening.

P

Paint
Architectural and household coatings.

Pavement
One or more layers of artificial construction for a road or runway.

Permeation/(Permeability)
The passage (or diffusion) of a gas, liquid or solid through a barrier without physically or chemically affecting it. (A property of a material which shows the degree to which it allows permeation to occur).

Permittivity
A parameter for cross-plane permeability of a geotextile.

Pitch
Residual petroleum product used in the manufacture of carbon fibres.

Phenoplast
Phenol-formaldehyde polymers, made by the reaction of phenol and formaldehyde - also known as Bakelite.

Phenoxy resin
A high molecular weight thermoplastic polyether based on bisphenol A and epichlorohydrin with bisphenol-A terminal groups.

Photochromic
Capability of changing heat transmittance characteristics according to ambient temperature swings. (See also Chromogenic, Electrochromic, Thermochromic and Thermotropic)

Pigments
Insoluble, finely ground materials (tiny particles) used to create a decorative effect that give paint the property of colour.

Plastic
Shaped and ready to use solid polymeric material containing various additives.

Plasticisers
Chemicals added to polymers to gain flexibility and resiliency.

Poison
A substance which by chemical action and at low dosage can kill or injure humans (and mammals).

Post-Cure
Application of (external) heat to bring a resin system to a stable state of cure in the shortest possible time.

Potentiating Effect
Where one material enhances the toxicity of the other.

Polyester resin
A thermosetting or thermoplastic polymeric material made by esterification of polybasic organic acids with polyhydric acids, in which ester groups are in the main chains. The aliphatic polyesters tend to be relatively soft, whereas the aromatic derivatives are usually hard and brittle or tough.

Polymer/polymerisation
High molecular weight compounds produced from low molecular weight species/(production reaction of polymers).

Polymer (see also co-polymer)
A substance, natural or synthetic, which can be represented bys at least two repeated monomer units.

Polymer foam (cellular polymers or cellular plastics)
Multi-phase material systems (composites) that consist of a polymer matrix and a fluid phase, the latter usually being a gas.

Polyol
A substance containing several hydroxyl groups. Diol, triols and tetrols contain 2, 3 or 4 hydroxyl groups, respectively.

Polyurethane (PU)
Polymeric substance containing many urethane linkages.

Polyisocyanate
A polyisocyanate contains more than one isocyanate group.

Polymer concrete
A composite material formed by polymerising a monomer and aggregate mixture (or a hardened mixture of various dry aggregates and a synthetic resin that is used as the bonding agent).

Polymer impregnated concrete (PIC)
Hardened portland cement concrete with impregnated monomer which is polymerised *in situ*.

Polymer Portland cement concrete (PPCC)
Portland cement concrete produced by replacing a specified portion of the mixing water with a latex (polymer emulsion).

Polyurethane resin (PU resin)
Resins that can be in different forms, (varying from hard, glossy, solvent-resistant coatings to abrasion and solvent-resistant rubbers, fibres and flexible-to-rigid foams), produced by the reaction of diisocyanates with a phenol, amine, hydroxyl or carboxyl compound.

Polyvinyl resin (polyvinylics, vinyl plastics)
Any resin derived from vinyl monomers.

Preform
The formation of an intermediate part that will subsequently be processed into the required part. (It is the process where glass mats are formed over a perforated screen like mould).

Prepreg
Intermediate mixed product of an uncured composite (with continuous unidirectional or woven fibres) with catalysed resin matrix material, ready for cure, usually in flexible sheet form.

Primary structural materials
Materials, which if the structure fails, can cause serious damage that cannot be repaired.

Protection
The use of a nonwoven geotextile to cushion a geomembrane to prevent it from getting punctured.

Pultrusion
A continuous manufacturing process for composite rods, tubes, and structural shapes having a constant cross-section.

Pyrolysis
Chemical decomposition.

R

R-value
A measure of resistance to heat flow. The higher the R value, the better the resistance and better insulating properties, which change considerably with density.

Radiation
Heat energy that is radiated across the air space and absorbed by another body, i.e., radiant energy of the sun which can be absorbed as heat by the human body.

Rebar
Polymer fibre reinforced concrete composite.

Residual monomer
The unpolymerised monomer that remains in a polymer after the polymerisation reaction is completed.

Resilient (floor)
A category of tile and sheet material characterised by its ability to return to its original form after compaction.

Resin
Solid or semi-solid organic polymeric products of high molecular weight, natural or synthetic origin with no definite melting points, which as a matrix binds together the reinforcement fibres.

Reinforcing agents
Solid inclusions of various types with different geometries (powders, flakes, fibres, fabric, etc.), used to reinforce the polymers. (See also Reinforcement)

Reinforcement
The use of reinforcing agents to impart tensile resistance to polymers. (See also Reinforcing agents)

Resilient
Material that characteristically 'bounces back' from the weight of objects that compress its surface. Vinyl flooring is also called 'resilient' flooring.

Revetment
Stones, rocks, concrete blocks or other materials used for the erosion protection of a soil surface.

Rigid polymer
A polymer with a modulus of 6.895 Pa.s or greater.

Riprap
Large stones used for purposes of revetment.

Roving
A collection of bundles of continuous fibre filaments, either as untwisted strands or as twisted yarn.

Rutting
Sunken track in road created over time by the passage of wheels.

S

Sandwich panels (SWP)
Layered structures with two thin, high modulus (metallic, concrete or polymeric) facings adhered to a lightweight core of foam (or honeycomb).

Sealant
Elastomeric substances used to seal or caulk, an opening, or expansion/contraction joints in building structures against wind and water.

Sealing
Impeding or obstructing the flow of liquid or gas by using geomembranes or spraying or impregnating the geotextile with bitumen or other mixes.

Secondary structural materials
Materials, which, if the structure fails, can only cause local damage that can be repaired.

Self-skinning
A foam reaction mixture which forms a skinned surface on being moulded at a specified temperature and pressure.

Semi-organic polymer
Polymers where chains contain carbon and heteroatoms.

Separation
Using a geosynthetic material to prevent the intermixing of soils of different sizes.

Sheet moulding compound (SMC)
A flat pre-preg material containing resin, glass-fibre and filler, which is covered on both sides with polyethylene (PE) or Nylon film, and is used for press-moulding.

Shellac
Is a natural resin produced by refining an insect (*Coccus lacca*) secretion.

Shrinkage
The decrease in dimensions of a moulded part through cooling.

Sick building syndrome (SBS)
The symptoms of an illness caused by toxic emissions inside a building.

Silicone resin
Polymer chains with alternating atoms of silicon and oxygen with organic substituents attached to silicon atoms.

Slab-on-Grade Construction
The usual method of constructing a structural slab-on-grade is to use a thickened slab. At the edges of the slab, where most of the load will be carried, the slab is thickened, the thickened portion being cast integrally with the rest of the slab. A slab-on-grade can also be constructed with grade beams supported on piers, piles or pedestal types of footings. However, this type of construction is generally not used for residential construction.

Slabstock
Rigid or flexible polyurethane foam made in the form of a continuous block, usually of approximately rectangular cross-section.

Slip agent
An additive added to the plastic, providing surface lubrication to lower the coefficient of friction by their gradual migration to the surface.

Stabiliser
Chemicals used to inhibit the reactions in plastics which can cause undesirable chemical degradation during processing and in use.

Static load
Any load remaining in a stationary position for long periods of time.

Stereospecific (polymer)
Polymer whose molecular structure has a definite spatial arrangement. Also known as stereoregular.

Structural elements
Elements that require proper mechanical performance (strength, stiffness, vibration damping ability, to withstand 'live' as well as 'dead' loads), which may or may not bear the load in the structure. (See also Primary/Secondary Structural Elements)

Structural foam
Components possessing skins and cellular cores, similar to structural sandwich panels.

Strand
A collection or bundle of continuous filaments.

Sub-base
A bed of material under the base of a road, to provide drainage or to strengthen the road.

Subgrade
The natural ground under the pavement or base layer of a road.

Superplasticiser
Admixture that reduces the mixing water requirement of a concrete with a given consistency by more than 12%.

Surfactant
Surface active materials (used to help in mixing incompatible components of the reaction mixture).

Surface impoundment
A waste disposal site for the deposit or treatment of waste water (liquid or with less than 5% solids by weight) onto or into land.

Syndiotactic (polymer)
A type of polymer molecule where groups of atoms that are not a part of the backbone structure are located in some symmetrical fashion above and below the atoms in the backbone chain, when the latter are in a single plane.

Synergistic effect/synergism
A phenomenon where the effect of a combination of two (additives) is greater than the effect of sum of the two.

Syntactic foams
Foams with hollow microspheres.

T

Tacticity
The regularity or symmetry in the molecular arrangement or structure of a polymer molecule.

Teflon
Dupont's trademark covering all of its fluorocarbon resins, including polytetrafluoroethylene (PTFE) and various copolymers.

Texturing
The artificial roughening of the surface of a geomembrane.

Thermal Conductance (C, with units W/m^2K)
The amount of heat that will pass through a given amount of material in a given amount of time, and with a unit temperature difference maintained between the surfaces of the material under uniform and steady conditions.

Thermal Resistance (R, with units of m^2K/W)
The ability of a material of particular thickness to resist heat flow. R is reciprocal of thermal conductance, C. It is also known as insulation strength

Thermal Conductivity (k, with units of W/m K)
The rate of heat transfer in any homogeneous material. A material with k = 1 means that a 1 m cube of this material transfers heat at a rate of 1 watt for every degree of temperature difference between opposite faces.

Thermal Resistivity (r, with units of mK/W)
Reciprocal of thermal conductivity, k.

Thermoplastics (Thermoplastic Polymers)
A polymer shaped by heating and cooling, or re-heating.
In this group, there are: acrylics, polymethylmethacrylate (PMMA)
acrylonitrile butadiene styrene (ABS), aromatic polyamides (PI),
cellulosics (CA, CAB, CAP, CN), ethylene vinyl acetate (EVA),
fluoroplastics (Teflon, PTFE and FEP), Nylons - polyamides - (PA),
polyacetals (POM), polyethylethylketone (PEEK), polybutene-1 (PB-1),
polycarbonate (PC), polyesters - thermoplastic - (PETP, PBT, PET),
polyethylene - high density (HDPE), - low densty (LDPE) and - linear low density (LLDPE),
polymethylpentene (PMP), polyphenylene oxide (PPO),
polyphenylene sulfide (PPS), polypropylene (PP), polystyrene - General Purpose (GPPS),
- high impact (HIPS), thermoplastic elastomers (TPE, TPR), polyvinyl chloride (PVC),
styrene acrylonitrile (SAN).

Thermosets (Thermosetting Polymers)
A polymer which is preshaped and that can not soften or melt by re-heating.
In this group, there are: alkyds (AMC), allylics (DAP, DAIP, ADC), epoxies (EP), furans,
melamines/urea [aminos] (MF, UF) phenolics (PF), polyester, unsaturated (Polyester-U),
polyurethane (cast elastomers) (PU) and vinyl esters.

Thermochromic material
A physical material containing a heat-sensitive ink which changes colour as it changes temperature. (See also Chromogenic, Electrochromic Photochromic, and Thermotropic)

Thermotropic polymer
A polymer that is capable of transforming from a glassy melt or crystalline state into a liquid crystalline state, at a particular temperature, without being diluted by a solvent.
(See also Chromogenic, Electrochromic Photochromic, and Thermochromic)

Thinner
An additive used in paints and varnishes to adjust the consistency for application.

Titanium dioxide
A white non-reactive and non-toxic pigment that provides the greatest hiding power of all white pigments.

Toxic agents
Chemical and physical agents that have adverse effects on living organisms.

Toxic effects (see also independent toxic effect, potentiating effect, and synergistic effect)

(Independent) Toxic Effect
Where one or more substances exert their own effect which is independent of the others, for example in the case of of a combination of toxins.

Toxicity
Deleterious or adverse biological effects elicited by a chemical, physical, or biological agent.

Toxicology
The science dealing with toxic agents.

Tow
An untwisted bundle of continuous filaments (usually carbon), typically designated by a number followed by K, which stands for a multiplication by 1,000, and indicates the number of filaments in it, e.g., 12K tow has 12,000 filaments.

Transmissivity
A parameter for in-plane permeability of a geotextile or drainage geocomposite.

U

U factor
The heat transfer coefficient or heat loss factor.

Urea-formaldehyde resin (UF resin, urea resin)
Condensation products of urea (or melamine) with formaldehyde that yields to a synthetic thermoset resin. It is also known as urea resin.

Urethane
An organic group characteristic for polyurethanes, produced from the reaction of diisocyanates, [i.e., toluene diisocyanate, (TDI)], with a phenol, amine or hydroxylic or carboxylic compound.

Unidirectional (UD) laminate
A reinforced polymer laminate in which, most of the fibres are oriented in the same direction.

Ultra violet light (UV)
It is the high frequency wavelengths of light beyond violet in the visible spectrum, with wavelengths ranging from approximately 3900 Å to the upper limits of x-rays. The most common UV source is the sun and this can cause the chemical breakdown of many polymeric materials to produce fumes or dusts in time.

UV Absorbers
Chemicals used to protect plastics against the harmful effects of UV light.

W

Warp
Dimensional distortion in a plastic object after moulding or other fabrication due to the release of moulded-in stresses.

Water reducing admixture (WRA)
Materials that have the primary function of producing concrete of a specified workability at a lower water:cement ratio.

Waterstop
A water stop is a metallic or non-metallic material that is embedded in the concrete on either side of the joint, for the full extend of the joint, forming a liquid tight diaphragm that does not allow the passage of fluid through the joint.

Water vapour transmission
The amount of water vapour passing through a given area and thickness of a plastic sheet or film in a given time, when the sheet (or film) is maintained at a constant temperature and when its faces are exposed to certain different relative humidities, the result of which is given as grams per 24 hours per m^2.

Wet wall
The wall in which the water and waste pipes are located.

Whiskers
Fibres with aspect ratios of 150-2500.

Wicking-in
Absorption of liquids into a material (in the paint, it is the absorption of paint into the

substrate).

Window
The word originating from the old Norse word, 'vindauga', which is a combination of 'vinder' (wind) and 'auga' (eye), hence meaning 'eye for the wind' or 'wind-eye', is one of the essential features of a home providing a bridge between the exteriors (nature) and interiors (man-made environment).

Workability of concrete
Ability of concrete to be placed, compacted and finished without harmful segregation.

Woven fabric/woven roving
Fabric produced by bidirectional interlacing strands or yarns/collection of uni-or bidirectionally oriented continuous strands.

V

Vapour Barrier
A layer through which water vapour cannot pass readily or at all.

Vehicle
Portion of a coating that includes all liquids and the binder.

Vent
A small hole (or shallow channel) in a mould which allows air or gas to exit as the moulding material enters.

Volatile organic compound (VOC)
Toxic gaseous emissions from solvents in paints and plasticisers from some plastics.

Y

Yarn
Continuously twisted fibres or strands suitable for weaving into fabrics.

Web Addresses of Interest

Societies/Agencies/Associations/Institutes

American Plastics Council	http://www.plastics.org www.AmericanPlasticsCouncil.org http://www.plasticsresource.com
US Environmental Protection Agency	www.epa.gov
National Paint & Coatings Association	www.paint.org
European Pultrusion Technology Association (EPTA)	www.pultruders.com
Alliance for Flexible Polyurethane Foam (AFPF)	http://www.AFPF.com
Alliance for the Polyurethanes Industry (API)	www.Polyurethane.org
Spray Polyurethane Foam Alliance	http://www.sprayfoam.org/
Polyisocyanurate Insulation Manufacturers Association	www.pima.org
The European Chemical Industry Council (CEFIC)	www.cefic.be
The European Diisocyanate and Polyol Producers Association (ISOPA)	www.isopa.org
The Construction Specifications Institute (CSI)	www.csinet.org
The American Chemical Society (ACS), Division of Polymer Chemistry	www.polyacs.org
The Society of Plastics Engineers (SPE)	www.4spe.org/
The Society of the Plastics Industry (SPI)	www.socplas.org
Sealant, Waterproofing and Restoration Institute (SWRI)	www.swrionline.org
Construction Industry Research and Information Association (CIRIA)	www.ciria.org.uk
Institution of Structural Engineers Study Group on Advanced Composites	www-civ.eng.cam.ac.uk/isegroup/study.htm

The Construction Specifications Institute (CSI)	www.csinet.org
International Council for Research and Innovation in Building and Construction (CIB)	www.cibworld.nl
Japanese Technical Evaluation Centre – Panel Report on Advanced Manufacturing Technology for Polymer Composite Structures in Japan	http://itri.loyola.edu/polymers
The Vinyl Institute	www.Vinylinfo.org
Composites Processing Association, UK	www.composites-proc-assoc.co.uk
The Composites Institute of Australia	www.compinst.asn.au

Safety/Environment

Plastics and the Environment (American Plastics Council)	www.Plasticsresource.com
Plastics and Your Health (American Plastics Council)	www.Plasticsinfo.org
Material Safety Data Sheets, Michigan State University	www.orcbs.msu.edu/pat/msdslinkmain.html
Phthalate Information Centre	www.phthalates.org
Dansk Phthalate Information	www.phthalater.dk
DEHP Information Centre	www.dehp-facts.com
Healthy Building Network	www.healthybuilding.net

General

Environmentally Preferable Purchasing Guide - Plastic Lumber (in structural applications)	http://www.swmcb.org/eppg/8_1.asp
SealantsandCoatings.com	www.sealantsandcoatings.com
Bisphenol-A	www.bisphenol-a.org
Vinyl By Design	www.vinylbydesign.com
Vinyl Council of Australia	www.vinyl.org.au
Alliance for the Polyurethanes Industry	www.polyurethane.org

Alliance for the Polyurethanes Industry - Building Codes, Standards, and Test Methods	www.polyurethane.org/standards/
Hands on Plastics Programme	www.HandsOnPlastics.com
Polystyrene Packaging Website	www.Polystyrene.org

Composites in Construction

Network Group for Composites in Construction (NGCC)	www.ngcc.org.uk
Advanced Polymeric Composites for Structural Applications in Construction (CoSACNet)	www.cosacnet.soton.ac.uk
Intelligent Sensing for Innovative Structures (ISIS)	www.isiscanada.com
Worldwide Composites Search Engine	www.wwcomposites.com
MatWeb – Materials Property database	www.matweb.com
About.com Composite materials	http://composite.about.com/mbody.htm
International Research on Advanced Composites in Construction (IRACC)	www.iper.net/co-force/iracchtm
ConFibreCrete (TMR.Network)	www.shef.ac.uk/~tmrnet

Abbreviations and Acronyms

4-PC	4-Phenylcyclohexane
ABS	Acrylonitrile-butadiene-styrene terpolymer
ACCS	Advanced Composite Construction System
ACM	Advanced composite materials (s)
ADEQ	Arizona Department of Environmental Quality
ADOT	Arizona Department of Transportation
AF	Aramid fibres
AFRP	Aramid-fibre-reinforced polymer composites
AIA	The American Institute of Architects
ANSI	American National Standards Institute
APE	Alkylphenol ethoxylate(s)
APME	Association of Plastic Manufacturers's in Europe
aPP	Atactic polypropylene
ARTM	Assisted RTM
ASA	Acrylonitrile-styrene-acrylonitrile copolymer
ASHRAE	American Society for Heating Refrigeration and Air Conditioning Engineering
ASSET	Applications of Smart Structures in Engineering and Technology
ASTM	The American Society for Testing and Materials
ASU	Arizona State University
ATBC	Acetyl tributyl citrate
BA	Butyl acrylate
BBP	Benzylbutylphthalate
BBRI	Belgian Building Research Institute
BD	Bi-directional
BMC	Bulk moulding compound(s)
BMI	Bismaleimide(s)

BPA	Bisphenol-A
BPO	Benzoyl peroxide
BRE	The Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BRI	Building related illness
BuProp	*n*-Butyl propionate
CA	Cellulose acetate
CAB	Cellulose acetate butyrate
CCA	Chromated copper arsenate
CD-ROM	Compact disk - read only memory(s)
CF	Carbon fibre (s)
CFC	Chlorofluorocarbon(s)
CFRP	Carbon-fibre-reinforced polymer composites
CIB	International Council for Research and Innovation in Building and Construction, The Netherlands
CMC	Carbon matrix composite(s)
CNS	Central nervous system
CO	Carbon monoxide
COTE	Committee on the Environment
CPCS	Consumer Products Safety Commission
CPE	Chlorinated polyethylene
CPVC	Chlorinated PVC(s)
CR	Chloroprene rubber
CSIRO	Commonwealth Scientific & Industrial Research Organisation, Australia
CSM	Chopped strand mat
CSPE	Chlorosulfonated polyethylene
CTE	Coefficient of thermal expansion
CTMP	Chemico-thermomechanical pulp fibre
DAP	Di-allyl-phthalate
DBP	Dibutylphthalate
DCPD	Dicyclopentadiene
DDS	4,4´-Sulfonyl dianiline

DDT	Dichlorodiphenyltrichloroethane
DEHA	Di(2-ethylhexyl) adipate
DEHP	Di(2-ethylhexyl) phthalate
DFT	Dry film thickness
DIDP	Di-isodecyl phthalate
DIHP	Di-isoheptyl phthalate
DINP	Di-isononyl phthalate
DIOP	Di-isooctyl phthalate
DMC	Dough moulding compound(s)
DNA	Deoxyribonucleic acid
DOA	Dioctyl adipate
DOE	Department of the Environment
DOP	Dioctyl phthalate
DP	Degree of polymerisation
DTPD	*N¢*, *N*-diaryl-paraphenylene diamine
DVB	Divinylbenzene
DVD	Digital video disk(s)
EB	Electron beam radiation
EBN	Environmental Building News
EBR	Externally bonded reinforcements
ECD	Endocrine disrupter(s)
ECH	Epichlorohydrin
ECPI	European Council for Plasticisers and Intermediates
EGC	Epigenetic carcinogens
E-GF	E-glass
EIP	Eco-industrial park(s)
EM	Electromagnetic
ENB	Ethylidene norbornene
EP	Epoxy polymer
EPA	Environmental Protection Agency
EPDM	Ethylene-propylene-diene terpolymer(s)
EPE	Expanded polyethylene
EPM	Ethylene-propylene monomer

EPR	Extended Producer Responsibility
EPS	Expanded polystyrene
E-PVC	Emulsion type PVC
ERA	Evaporation rate analysis
EU	European Union
EVA	Ethylene vinyl acetate
FEF	Fast extrusion furnace
FFT	Foiled FibrePur Technology
FGR	Fibre glass reinforced
FR	Fibre-reinforced
FRC	Fibre reinforced composite(s)
FRP	Fibre-reinforced plastic(s)
GDP	Gross domestic product
GF	Glass fibre(s)
GFP	Glass fibre reinforced polymer
GFRP	Glass-fibre reinforced plastic
GIFT	Goldsworthy Innovative Fabrication Technology
GRP	Glass reinforced plastic(s)
GWP	Global warming potential
HALS	Hindered amine light stabilisers
HAM	Heat, air and moisture
HAP	Hazardous air pollutant
HC	Hybrid composites (s)
HCFC	Hydrochlorofluorocarbon(s)
HCM	Hybrid composite materials (s)
HCN	Hydrogen cyanide
HDI	Hexamethylene diisocyanate
HDPE	High-density polyethylene
HFC	Hydrofluorocarbon
HI	Heterogeneity index
HIPS	High-impact polystyrene

HM	High modulus
HMTA	Hexamethylenetetramine
HRV	Heat recovery ventilator(s)
HRWRA	High-range water reducing admixture(s)
HT	High tensile
HVAC	Heating, ventilation and air conditioning system
IAQ	Indoor air quality
IARC	International Agency for Research on Cancer
IIATP	International Institue of Polymer Arts and Techniques
IM	Intermediate modulus
IPN	Interpenetrating networks
iPP	Isotactic polypropylene
IQ	Intelligence quotient
IR	Infra-red
IRHD	International Rubber Hardness Degrees
ISO	International Standards Organisation
L/D	Length:diameter ratio
LC	Liquid crystalline
LCC	Life cycle costing(s)
LD_{50}	Median lethal dose
LDPE	Low-density polyethylene
LED	Light-emitting diode(s)
LEED	Leadership in Energy and Environmental Design
LLDPE	Linear low-density polyethylene
LMC	Latex-modified concrete
LOI	Limited oxygen index
LSOH	Low-smoke, zero halogen
M	Monomer molecule
MA	Maleic anhydride
MBS	Methacrylate-butadiene-styrene (s)
MBT	2-Mercapto benzothiazole

MC	Moulding compound(s)
MDA	4,4′-Methylene-dianiline
MDF	Medium density fibreboard
MDI	Diphenylmethane di-isocyanate
MDPE	Medium-density polyethylene
MEKP	Methylethylketone peroxide
MF	Melamine-formaldehyde
MLD	Median lethal dose
MMA	Methyl methacrylate
MMC	Metal matrix composite(s)
MNAK	Methyl *n*-amyl ketone
MOE	Modulus of elasticity
MOPVC	Molecularly oriented PVC(s)
MOR	Modulus of rupture
MRI	Magnetic resonance imaging
MSW	Municipal solid waste
MUF	Melamine-urea-formaldehyde
MW	Molecular weight
NASA	National Aeronautics and Space Administration
NAU	Northern Arizona University
NBR	Acrylonitrile-butadiene rubber
NMR	Nuclear magnetic resonance
NR	Natural rubber
NSM	Near surface mounted bars
OBPA	10-10′-Oxybisphenoxarsine
ODP	Ozone depletion potential
OITO	2-*N*-octyl-4-isothiazolin-3-one
OSB	Oriented strandboard
OSHA	Occupational Safety and Health Administration
PA	Polyamide(s)
PAE	Polyacrylic ester
PAH	Polycyclic aromatic hydrocarbon

PAN	Polyacrylonitrile
PATH	Partnership for Advancing Technology in Housing
PB	Polybutylene
PBO	Paraphenylene polybenzobisoxazole
Pbw	Parts by weight
PBZ	Polybenzazoles
PC	Polycarbonate(s)
PC	Polymer cement
PCB	Polychlorinated biphenyl(s)
PCC	Polymer modified cement concrete
PCDD	Polychlorinated dibenzo-*p*-dioxin(s)
PCDF	Polychlorinated dibenzofuran(s)
PE	Polyethylene(s)
PEEK	Poly-ether-ether-ketone
PEI	Poly ether imide
PES	Saturated polyester
PET	Polyethylene terephthalate
PF	Phenol formaldehyde
phr	Parts per hundred rubber
PIC	Polymer impregnated concrete
PIR	Polyisocyanurate(s)
PMC	Polymer matrix composite(s)
PMMA	Poly(methyl methacrylate)
PMR	Polymerisation of monomer reactant(s)
POM	Polyoxymethylene
PP	Polypropylene
PPCC	Polymer portland cement concrete
PPD	*Para*-phenyleneterephtalamide
PPO	Polyphenylene oxide
PPRC	Pollution Prevention Resource Center
PPS	Polyphenylene sulfide
PS	Polystyrene(s)
PTFE	Poly(tetrafluoroethylene)
PTT	Polytrimethylene terephthalate

PU	Polyurethane(s)
PUR	Polyurethane rubber
PVA	Poly(vinyl alcohol)
PVAc	Polyvinyl acetate
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride(s)
PVC-P	Plasticised PVC
PVC-U	Unplasticised PVC
PVDC	Polyvinylidene chloride
PVDF	Polyvinylidene fluoride
PZT	Piezoelectric zirconate titanate
RC	Reinforced concrete
RH	Relative humidity
RHR	Rate of heat release
RIFT	Resin infusion under flexible tooling
RIM	Reaction injection moulding (s)
RP	Reinforced plastic(s)
RPL	Recycled plastic lumber
RPL-U	Unreinforced RPL
rpm	Revolutions per minute
RRIM	Reinforced reaction injection moulding
RTM	Resin transfer moulding
SAE	Poly(styrene-acrylic ester)
SAN	Styrene-acrylonitrile
SBR	Styrene-butadiene rubber
SBS	Sick Building Syndrome
S-B-S	Styrene-butadiene-styrene
SEM	Scanning electron microscope
SIP	Structural insulated panel(s)
SIS	Styrene-isoprene-styrene
SMC	Sheet moulding compound(s)
SPF	Spray PU foam

SRF	Semi-reinforcing furnace (carbon black)
SRIM	Structural reaction injection moulding
SSSE	Solid state shear extrusion
SSWP	Structural sandwich panel
SWP	Sandwich panel(s)
TCP	Tricresyl phosphate
TDI	Toluene diisocyanate
TEC	Thermal expansion coefficient(s)
TEHTM	Tri-(2-ethylhexyl) trimellitate
TERTN	Thermal expansion RTM
TET	Triethyl-tin
T_g	Glass transition temperature(s)
TGMDA	Tetraglycidyl methylene dianiline
TLV	Threshold limit value(s)
T_m	Crystalline melting temperature
TMA	Trimellitic anhydride
TMPTMA	Trimethylolpropane trimethacrylate
TMT	Trimethyl tin
TMTDS	Tetramethyl thiuram disulfide
ToE	Tonnes of oil equivalent
TOTM	Trioctyl trimellitate
TS	Tensile strength
TTT	Time-temperature-transformation
TVOC	Total VOC
UD	Unidirectional
UF	Urea-formaldehyde
UHMWPE	Ultra high molecular weight PE
UMR	University of Missouri - Rolla
UP	Unsaturated polymer resin
uPES	Unsaturated polyester
USGBC	US Green Building Council
UTS	University of Technology, Sydney
UV	Ultraviolet

VAc	Vinyl acetate
VC	Vinyl chloride
VCM	Vinyl chloride monomer
VE	Vinyl ester resin
VLDPE	Very-low density PE
VOC	Volatile organic compound(s)
VR	Vapour retarder(s)
W/C	Water to cement ratio
WHO	World Health Organisation
WPC	Wood-plastic composites (s)
WRA	WWWater reducing admixture
XLPE	Crosslinked polyethylene

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