The Utilization of Slag in Civil Infrastructure Construction

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This book is dedicated to my wife Jane for her love
and wholehearted support

Preface

In the late 1980s, when I was doing my PhD studies, the only technical book available expounding on slag production, process, and utilization was Dr. A. R. Lee's *Blast Furnace and Steel Slag–Production, Properties and Uses*, published in 1974. During the past decades, although numerous research reports and papers have been published, there has been no publication of books on the subject. The seeds of inspiration for this book were planted during this time. Providentially, I was contacted by Gwen Jones, Senior Manager of Elsevier, about the possibility of writing a professional book on slag utilization; I accepted with pleasure.

Over the years, I have gained research and practical experience with slag utilization in industry and in academia. I have also been involved in slag utilization projects in several countries, which have resulted in a number of technical reports and papers on the subject. In order to reflect the most current utilization of slag technology around the world, I have reviewed substantial literature from English, French, Spanish, German, Chinese, Japanese, and Russian sources on various slags.

This technical text strives to integrate the practice, research, and theory of slag utilization, including the production and processing of slags. This information can be applied as a solution for problems encountered during the utilization of ferrous, nonferrous, and nonmetallurgical slags. It should be noted that slag utilization, in keeping with other aspects of industrial materials recycling, is a very broad subject covering a wide range of topics. The topics of interest covered include: production and smelting processes for metals; chemical and physical properties of slags; pretreatment and posttreatment (chemical and physical) technology for enhancing slag properties; potential environmental impacts; mechanisms of potential expansion (particularly steel slag); special testing methods and characteristics; slag processing for aggregate and cementitious applications; suitability of slags for use in specific applications; overall properties of materials containing slags; and last, but not least, commercialization and economics.

The ultimate purpose of this book is to facilitate the use of slags through the development of quality, value-added end products containing slag. It is my hope that this book presents the reader with practical solutions to the problems often encountered in the day-to-day utilization of slags, and in research on slag production and utilization. I have emphasized the importance of establishing performance relationships, based on the intrinsic properties of slag, between the slag and commercially viable aggregate, and cementitious and bulk uses.

It is also my intention that, through the information I have presented, the use of one type of slag will be extended toward other slags, as appropriate, by taking them from the research and trial stage into commercialization. Most importantly, I shall attempt to clarify some concerns previously raised over specific slag types, and their uses, so that new or revised standards for various uses of slag can be established.

The subject of slag utilization is quite dynamic, and it will be necessary to incorporate new information through updates. It is important that the reader monitor the literature on slag utilization in order to keep current.

I wish to acknowledge the assistance provided by my industry colleagues. Particular thanks are extended to Ms. Karen Kiggins, President of the National Slag Association, for encouragement and providing valuable materials; Mr. John Yzenas, Technical Director of Edward C. Levy Corporation, for reviewing chapters and discussing the contents of this book; Mr. Peter Mazzarella of the Harsco Corporation, Dr. D. Xie of CSIRO, Australia, Mr. Billy Troxler of Troxler Electronic Laboratories, and Dr. Patrick Zhang of the FIPR Institute, for providing illustrations and technical information; Dr. Ioannis Liapis of AEIFOROS Metal Processing SA, Greece, and Mr. Nick Jones of the Harsco Corporation, South Yorkshire, UK, for providing information for case studies in the book.

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Notations and abbreviated formulae

A	Al_2O_3
A	area
A_{ms}	area of diametrical section of a steel slag particle ($\pi d^2/4$)
A_s	whole surface area of a steel slag particle (πd^2)
B	basicity
C	CaO
C_o	content of ordinary Portland cement clinker (by wt%)
d	crystal surface distance
d	diameter of slag aggregate particle (in.)
d	mean particle size of sample (mm)
d	mean diagonal length (mm)
d	nominal particle size of slag aggregate
d	particle size of next grade
D	denseness of slag (%, γ_o/γ_s)
D	particle size of preceding particle grade
D	reading from load cell
D_a	practical volume ratio of next particle grade
D_o	theoretical volume ratio of next particle grade (the ratio of loose volume weight to apparent volume weight)
E	volume expansion (%)
E_l	volume expansion of lime (%)
E_s	volume expansion of steel slag (%)
E_{smax}	expansion force when volume expansion is zero
E_{smin}	expansion force when the volume expansion is maximum
E_v	volume expansion when surcharge weight is zero
f-CaO	free CaO
f_{eus}	expansion force of slag, generated by unstable slag in concrete
f_{ex}	expansion force per unit volume produced by slag particles
F	allowable tensile stress of a rigid matrix
F	expansion force
f	free lime content (by wt%)
F	free lime content
F	Fe_2O_3
F_c	f-CaO content in ordinary Portland cement clinker (by wt%)
f_{ec}	expansion force produced by the slag particle in one cubic meter of concrete
f_{ex}	expansion force produced by slag particles
f_s	f-CaO content in slag
F_s	free CaO content in slag (by wt%)

f_{ss}	expansion force from a single slag particle (N)
H	H_2O
hcp	hardened cement paste
H_v	hardness
I	initial reading in experiment
K	stability factor
k	safety factor
N_c	number of slag particles cracked or powdered
N_t	total number of slag particles in the disruption test
p	steam pressure (kg/cm^2)
P	load (g)
P_e	expansion force of compacted mass of slag (or apparent volume expansion force) (N)
P_{es}	expansion force from single slag particle (N)
P_{ev}	virtual expansion force produced by slag per cubic meter of concrete (N)
P_t	tension force produced from resultant force of normal volume stress (N)
R	slag particle disruption ratio (%)
RO	mixed-crystal of metallic oxides
S	surcharge of slag sample
S	powdering ratio (%)
S	minimum slope
S_c	content of BOF slag (by wt%)
S_c	content of slag
$\overline{S}$	SO_3
t	the gap distance of preceding grade (ie, the particle size of next grade)
t	treating time (h)
T	expansion force measured from slag constrained in a mold
T	external loading
T_1	powdering ratio, <0.3 mm
T_2	powdering ratio, <4.75 mm
T_s	side expansion force
TG	thermogravimetry
V	volume of bulk slag
V_a	volume of slag aggregate particle per cubic meter of concrete (m^3)
V_c	volume of compacted mass slag, apparent volume (m^3)
V_{ea}	actual volume occupied by expanded slag (m^3)
V_o	apparent total volume of slag (m^3)
V_s	volume of spherical slag aggregate particle ($\pi d^3/6$)
V_{sc}	volume of slag aggregate in one cubic meter of concrete
V_{se}	actual volume of expanded slag particle in concrete
V_{sl}	given volume of compacted slag particles
V_{ss}	volume of a single slag particle, spherical ($\pi d^3/6$)
ΔV	volume increase in steel slag
w	degree of hydration (%)
γ_l	specific gravity of lime (g/cm^3)
γ_o	bulk density of steel slag (g/cm^3)
γ_s	specific gravity of steel slag (g/cm^3)
μ	Poisson's ratio
$[\sigma]$	allowable tensile stress of cement mortar at given age (MPa)
σ_d	dangerous stress (MPa)

$\boldsymbol{\sigma}_{\mathrm{e}}$	expansion force of compacted mass steel slag per unit volume (N/m^3)
$\boldsymbol{\sigma}_{\mathrm{euv}}$	volume expansion force from steel slag which are unstable (N/m^3)
$\boldsymbol{\sigma}_{\mathrm{n}}$	normal stress acting on the surface of one steel slag particle (MPa)
$\boldsymbol{\sigma}_{\mathrm{t}}$	maximum tension stress of steel slag acting on potential disrupting region (MPa)
$\boldsymbol{\sigma}_{\mathrm{v}}$	virtual expansion stress
$\boldsymbol{\sigma}_{\mathrm{v}}$	virtual volume force (N/m^3)
$\boldsymbol{\sigma}_{\mathrm{vs}}$	side virtual expansion stress
$\boldsymbol{\sigma}_{\mathrm{vs}}$	virtual side expansion stress (MPa)
$\boldsymbol{\sigma}_{x}$	normal stress
$\boldsymbol{\sigma}_{y}$	normal stress
$\boldsymbol{\sigma}_{\theta}$	normal stress
ϕ	filling factor, volume of spherical solid particles under tightly compacted condition, assume 67%

List of acronyms

3RS	reduce, reuse, and recycle
AAR	alkali-aggregate reactivity
AASHTO	American Association of State Highway and Transportation Officials
AAV	aggregate abrasion value
AC	asphalt cement
ACAA	American Coal Ash Association
ACBFS	air-cooled blast furnace slag
ACV	aggregate crushed value
AISE	Association of Iron and Steel Engineers
AISI	American Iron and Steel Institute
ALT-MAT	Alternative Materials Program
APA	asphalt pavement analyzer
ARB	acid resisting brick
AREA	American Railway Engineering Association
ASTM	American Society for Testing and Materials
ATP	adenosine triphosphate
AUSIMM	The Australian Institute of Mining and Metallurgy
B2	Binary basicity
BF	blast furnace
BFS	blast furnace slag
BOF	basic oxygen furnace
BRD	bulk relative density
BSI	British Standards Institution
BT	Total basicity
Btu	British thermal unit
BUD	beneficial use determination
CAA	Clean Air Act
CAER	Center for Applied Energy Research
CBR	California bearing ratio
CCP	coal combustion product
CDW	construction and demolition waste
CEAF	concrete with EAF slag
CEN	The European Committee for Standardization
CERCLA	Comprehensive Response, Compensation and Liability Act of 1980 (Superfund)
CIR	cold in place recycling
CKD	cement kiln dust
CNR	Canadian National Railways
CR	creep rate

CSH	calcium-silicate-hydrate
C-SHRP	Canadian Strategic Highway Research Program
CSIRO	Commonwealth Scientific and Industrial Research Organization
CWA	Clean Water Act
DBM	dense bitumen macadam
DIN	Deutsches Institut für Normung/German Institute for Standardization
DNA	deoxyribonucleic acid
DOT	Department of Transportation
DTA	differential thermal analysis
EAF	electric arc furnace
ECOBA	European Coal Combustion Products Association
EDS	energy dispersive X-ray spectroscopy
EDX	energy dispersive X-ray spectroscopy
EDXA	energy dispersive X-ray analysis
EI	elongation index
EN	European Standards
EoW	end-of-waste
EP	emergency pit
EPA	Environmental Protection Agency
EPCRA	Emergency Planning and Community Right-To-Know Act
ESAL	equivalent single axle load
ESS	Egyptian Standard Specifications
EU	European Union
EUROSLAG	European Slag Association
EWC	The European Waste Catalogue
FEhS	Institut für Baustoff-Forschung/Research Institute for Iron and Steel Slags, Germany
FGD	flue gas desulfurization
FHWA	Federal Highway Administration
FI	Flakiness index
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
FIPR	Florida Industrial Phosphate Research
FRAP	fractionated reclaimed asphalt pavement
FT	fluid temperature
GBFQR	granite-basalt fine quarry residue
GBFS	granulated blast-furnace slag
GGBFS	ground granulated blast furnace slag
GLZS	granulated lead-zinc slag
GTR	ground tire rubber
HCFA	high calcium fly ash
HCP	hardened cement paste
HFST	high friction surface treatments
HMA	hotmix asphalt
HSWA	Hazardous and Solid Waste Amendments
HT	hemispherical temperature
ICSS	instant chilled steel slag
IDT	initial deformation temperature
IEA	International Energy Agency
INSG	International Nickel Study Group

ISF	imperial smelting furnace
ISP	Imperial Smelting Process
ISSA	International Slurry Surfacing Association
ITS	indirect tensile strength
ITZ	interface transition zone
IZA	International Zinc Association
JIS	Japanese Industrial Standard
KFQR	kaolin fine quarry residue
KHI	Kawasaki Heavy Industries, Ltd.
LA	Los Angeles
LAGA	Länderarbeitsgemeinschaft Abfall, an acknowledged official standard for environmental authorities in Germany
LCA	Life-cycle assessment
LCCA	life-cycle cost analysis
LD	Linz-Donawitz
LF	ladle furnace
LOI	loss of ignition
L/S	liquid-to-solid ratio
MDD	maximum dry density
MIP	mercury intrusion porosimetry
MNRO	Ministry of Natural Resource of Ontario
MR	resilient modulus
M/S	magnesia-to-silica ratio
MSW	municipal solid waste
MSWI	municipal solid waste incinerator
MTD	material transfer device
NAPA	National Asphalt Pavement Association
NEPA	National Environmental Policy Act
NSA	National Slag Association
NSA	National Stone Association
OBM	oxygen bodenblasen Maxhuette
OCS	oxygen converter slag
OECD	Organization for Economic Cooperation and Development
OGFC	open grade friction course
OPA	Oil Pollution Control Act of 1990
OPC	ordinary Portland cement
OSHA	Occupational Safety and Health Act
PCA	Portland Cement Association
PCC	Portland cement concrete
PFC	porous friction course
PG	performance graded
PM2.5	particulate matter with a diameter less than or equal to 2.5 um
PMA	polymer modified asphalt
PP	polypropylene
PPA	Pollution Prevention Act
PSSBFC	Portland clinker-steelmaking slag-blast furnace slag cement
PSV	polished stoned value
QA	quality assurance
Q-BOP	quick-quiet basic oxygen process

QC	quality control
QMS	quality management system
QXRD	quantitative X-ray diffraction
RAP	reclaimed asphalt pavement
RCA	recycled concrete aggregate
RCRA	Resource Recovery and Conservation Act
RO	solid solution of minerals
SBS	styrene-butadiene-styrene
SCC	self-compacting concrete
SCM	secant creep modulus
SCM	supplementary cementitious materials
SDWA	Safe Drinking Water Act
SEM	scanning electron microscope
SFS	steel furnace slag
SHRP	strategic highway research program
SMA	stone (matrix) asphalt
SMI	Sumitomo Metal Industries, Ltd.
SMR	stiffness modulus ratio
SN	Skid number
SSBC	steel slag blended cement
ST	softening temperature
TCEQ	Texas Commission on Environmental Quality
TCLP	toxicity characteristic leachate procedure
TFV	ten percent fines value
TQM	total quality management
TRB	Transportation Research Board
TSCA	Toxic Substances Control Act
USGS	US Geological Survey
VMA	voids in the aggregates
WBBS	wet-bottom boiler slag
W/C	water-to-cement (cementitious material) ratio
WFD	The European Waste Framework Directive
WMA	warm-mix asphalt
WRAP	Waste & Resources Action Programmme (UK)
WTE	waste-to-energy
XEDS	energy dispersive X-ray analysis
XRD	X-ray diffraction

SI* (modern metric) conversion factors

Approximate Conversions to SI Units				
Symbol	**When you know**	**Multiply by**	**To find**	**Symbol**
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
Area				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
Volume				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
Note: Volumes greater than 1,000 L shall be shown in m^3.				
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	Megagrams (or "metric tons", "tonnes")	Mg (or "t")
Temperatures (exact degrees)				
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C

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* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

Approximate Conversions to SI Units				
Symbol	**When you know**	**Multiply by**	**To find**	**Symbol**
		Illumination		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units				
Symbol	**When you know**	**Multiply by**	**To find**	**Symbol**
		Length		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		Area		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		Volume		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		Mass		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	Megagrams (or “metric tons”, “tonnes”)	1.103	short tons (2,000 lb)	T
		Temperature (exact degrees)		
°C	Celsius	1.8C + 32	Fahrenheit	°F

Approximate Conversions from SI Units				
Symbol	**When you know**	**Multiply by**	**To find**	**Symbol**
Illumination				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
Force and Pressure or Stress				
N	newtons	0.225	poundforce	lbf
kPa	kilopascales	0.145	poundforce per square inch	lbf/in^2

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Introduction

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1.1 Introduction to slag utilization in civil infrastructure construction

Ferrous, nonferrous, and nonmetallurgical slags are the family of large volume, molten coproducts or by-products of metallurgical or special processes (high-temperature incineration, for instance) that are subsequently cooled (solidified) through various processes forming materials with a wide range of aggregate and cementitious uses. The appropriate use of slags is very important, both to reduce potential environmental impacts and for natural resources sustainability, with a financial return rather than disposal costs. The primary theme throughout this book is the overall technology and strategy of transferring a slag from the "waste" stream, into a useful material "resource" stream, including the value-added utilization of slags, particularly applications that recover the considerable invested process energy, such as supplementary cementitious material uses, and the appropriate utilization of each slag type and end product requirements. Unlike conventional aggregates and cementitious materials, which are produced from virgin natural materials under carefully controlled process conditions to meet demand, slag products are produced by using discharged coproducts or by-products that can result in considerable compositional and physical variability and special handling, processing, and quality control requirements for utilization.

Ferrous (iron and steel) and nonferrous (copper, nickel, lead, zinc, etc.) will probably continue to be the most commonly used structural and functional materials in terms of quantity. Due to the large quantities of resulting slag production worldwide and the potential environmental impact, and that, more importantly, research and practical experience have proved many successful slag uses, it is not acceptable to simply dispose of slags in landfills or waste stockpiles. Proactively responding to growing environmental globalization concerns and natural resource shortages (both bulk and energy materials), scientists and engineers have been researching and developing a wide range of environmentally acceptable, technically sound, and positive economic-return uses for slags. Policymakers have promulgated some pertinent regulations. The utilization of ferrous, nonferrous, and nonmetallurgical slags has become an important aspect of environment protection and natural resources conservation. This growing positive slag utilization response to the key socioenvironmental and sustainable development concerns results in both responsible stewardship of the overall metallurgical or special process and a positive contribution to the process economics.

The utilization of slag can be traced back to the early developmental stages of metallurgical processes such as iron production. Using slag as a material, rather than simply discarding it as a waste, has actually been a coproduct issue since the early ages of smelting technology. From the history of slag utilization, it has been found that the use of a slag has followed a "cycle": find an application (use); encounter performance

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problems during the application; determine the cause(s) of the problem(s); solve the problem(s); and achieve a technically sound utilization. This continues to be the present slag utilization route in construction applications such as aggregate or cementitious applications. The direct theme throughout, of value added and appropriate slag utilization, provides the experience factors to expedite the development and implementation of slag uses.

When speaking of slag, many people have become used to considering it as just a waste, and slag is still unfortunately a derogatory term in some cultures. It is noted that this comes from old-fashioned conservative opinion on recycled- or by-products and/or wrongful regulations. However, more often now, particularly in the metallurgical process and construction industries, slags are recognized as valuable coproducts or nontraditional material and a resource with value-added utilization potential. This change reflects the continuing development of a full range of aggregate and cementitious uses for many slag types; slag waste streams have become materials resource streams.

A wide range of excellent and informative materials science and construction materials technology papers (unfortunately, few specific slag-type professional texts) have been published and considerable advances in slag utilization have been, and are being made. However, an integrated professional text covering the production, processing, and utilization of the wide range of ferrous, nonferrous, and nonmetallurgical slags has not been published to date. One of the reasons appears to be that material scientists and engineers who try to use a specific slag type, from an individual source, for an aggregate or cementitious application are not conversant with slag production, processing, and specific compositional and physical properties, intrinsic variability of the slag, and the significant differences in a slag type (steel slags, for instance) from different sources. In contrast, the metallurgical engineer who is an expert and experienced with the specific compositional and physical features of the slag, given their importance to the primary process, often is not familiar with the range of performance requirements for the use of the slag as an aggregate or cementitious material. Therefore, a professional text dealing with the technology of slag utilization is very important to bridge the research and development slag utilization activities of both the slag producers and potential slag users. Hopefully the integration of the technical literature and practical utilization technology throughout this volume, as a slag utilization resource, will expedite this producer-user bridge.

While this professional text deals with the production of various mineral products and the resulting coproduct or by-product slags, its focus is on slag utilization, its technology, methodology, and strategy of utilization, which requires a clear understanding of the basic properties of various slags and how its use in the end product will be technically sound, environmentally friendly, and economical. For this reason, considerable detail is devoted to these fundamentals with an explanation of the specific characteristics of testing and specification requirements.

It should be remembered that slags often have some common physical properties, chemical compositions, and characteristics; for example the grindability of granulated iron blast furnace, copper, and nickel slags. Therefore, findings for one slag type can often be extended to another slag with careful testing and verification of the slag's characteristics and the end materials' requirements, properties, and use. For example, the physical properties and chemical characteristics similarities between granulated copper and nickel slags results in similar usability criteria for blended cement manufacture.

It is necessary to define the term *slag* as used throughout. In a strict and narrow sense, slag is the molten fused “agglomerate” that separates during metal smelting and “floats” on the surface of the molten metal. As the term has also been used extensively in other nonmetallurgical processes for by-products applications, such as boiler slag from coal combustion and incinerator slag from waste incineration, nonmetallurgical process slags are included, which extends the slag definition to the broadest content.

The ultimate purpose of this professional text is to facilitate the use of slags through the development of quality, value-added end products containing slag, particularly the uses that recover the inherent energy content of the slag. The reader is presented with practical solutions to the problems often encountered in the day-to-day utilization of slags, the potential areas to explore in future research, and other positive experiences on various uses of slag. The importance of establishing the performance relationships, based on the slag's intrinsic properties, between the slag and commercially viable aggregate and cementitious uses is emphasized. It is anticipated that this professional text will benefit readers from the mining and metallurgy industries, chemical processing industry, civil engineering, aggregate production, building materials manufacturing, and educational and research institutions, particularly those who are exploring in the fascinating world of slag technology and utilization.

The utilization of slag in construction forms part of an overall strategy to optimize the utilization of available material resources—selective and more efficient use, conservation, beneficiation, new materials and methods, more use of residuals and by-products—that must be coupled with environment, sustainability, and energy consideration.

Clearly, the increased beneficial utilization of slags will make a positive environmental and sustainable development contribution to our challenged Earth.

1.2 Sustainability in construction, mining, and mineral production

Global climate change is the critical challenge human beings are facing on Earth in the 21st century. Climate change is caused by human activities releasing an overabundance of greenhouse gases into the atmosphere. Construction is one of the largest industries in the world. The construction industry constitutes around one-tenth of gross domestic product worldwide. In the United States, the construction industry is a major player in the nation's economy, contributing over $1 trillion including $770.4 billion of private construction and $316.6 billion in the public sector as of December 2008. Construction activities consume tremendous amounts of materials, including cement, concrete, aggregate, steel, nonferrous metals, and other inorganic nonmetallic materials, which are made from winning and processing natural ores and minerals. During this process, a huge amount energy is used, and greenhouse gas emission takes place. Reuse and recycle industrial and municipal coproducts and by-products can significantly save natural resources and contribute to sustainability in environmental, social, and economic aspects. The benefits of sustainable design and construction offer the potential to change the way in which we as humans face the challenges in the future. These challenges are not insignificant.

The mine industry has been the focus of environmental and social controversy. Mining impacts are many and varied. It is not uncommon that economically valuable mineral deposits do not occur below low-value surface environments, which are sometimes located in or near ecological reserves and protected areas.

Pressures on the environment from mineral extraction, mine waste, and related emissions have increased because mining has generally moved from small underground to large surface mining, and the number of mines has increased. Increased amounts of extracted minerals and waste rock, and the liberation of elements such as toxic metals and sulfur have increased global pollutant flows and, hence, environmental pressures. In terms of emissions, the mining industry is not unlike other industries, but as mining extracts, nonrenewable resources, easily accessible mineral reserves diminish over time; consequently, mining projects often last only 10–20 years, although occasionally longer (Spitz & Trudinger, 2009).

Mining almost always incurs extensive upfront development costs before actual ore extraction commences and the financial and operational responsibilities of mine owners continue after the mined resource is exhausted.

Pollution occurs due to extracted minerals and waste, as does altered physical–chemical conditions at the mine site.

In terms of response, perhaps the most important reality of mining is that "zero impact" is essentially impossible. However, societies can respond to mining and mining-induced changes in a variety of ways. One is the reduction of demand for minerals through substitution of traditional materials with synthetic ones. Demand can be further reduced by product recycling; by reworking of mineral wastes as secondary resources; and by use of material efficient technologies. Although necessarily long term, ultimately such measures can relieve pressure on the environment. Overall, the state of the environment can be improved by appropriate environmental management (Spitz & Trudinger, 2009).

In the cement industry, a large percentage of the weight of limestone is released as CO_2. In addition to CO_2 release and energy use, mining of limestone, the major raw material in cement, can cause habitat destruction, increased runoff, and pollutant release to the air and water. Some limestone mining operations are abandoning open-pit mining techniques in favor of underground mining. This technique may reduce some habitat and pollution impacts yet may increase cost (Calkins, 2009).

Also, the production of cement is an energy-intensive process using primarily fossil fuel sources. Cement comprises about 10% of a typical concrete mix but accounts for 92% of its energy demand. An average of almost 5 million Btus is used per tonne of clinker. In 2004, the cement sector consumed 422 trillion Btus of energy, almost 2% of total energy consumption by US manufacturing.

Emissions from Portland cement manufacturing include carbon dioxide (CO_2), particulate matter, carbon monoxide (CO), sulfur oxides (SO_x), nitrogen oxides (NO_x), total hydrocarbons and hydrogen chloride (HCl), and fine particles of PM2.5 (particulate matter with a diameter less than or equal to 2.5 μm) are the greatest cause for concern as they have the greatest negative impact on human health.

Aggregates, which make up between 60% and 75% of the concrete volume, are either mined or manufactured. The primary impacts of aggregate extraction and processing are habitat alteration and fugitive dust. It is difficult to capture dust in operations of mining and blasting, quarry roads, loading and unloading, crushing, screening, and storage piles. Primary impacts of crushed rock, aside from mining impacts, stem from fugitive dust released during crushing and screening operations. Processing of aggregates, particularly the commonly used silica sand, releases particulates into the air that can cause eye and respiratory tract irritations in humans.

Mining, dredging, and extraction of sand and gravel alter plant and animal habitats and contribute to soil erosion and air and water pollution. Mining for sand and gravel near or in water bodies causes sedimentation and pollution in water and disrupts aquatic habitats. The operation of mining equipment consumes energy and releases emissions from internal combustion engines. Energy to produce coarse and fine aggregates from crushed rock is estimated by the Portland Cement Association (PCA)'s Life Cycle Inventory to be 35,440 kJ per tonne. The energy to produce coarse and fine aggregate from uncrushed aggregate is 23,190 kJ per tonne (Medgar, Nisbet, & Van Geem, 2006).

The concept of sustainability has gained popular momentum over the last 20 years. The goals of sustainability are to enable all people to meet their basic needs and improve their quality of life, while ensuring that the natural systems, resources, and diversity upon which they depend are maintained and enhanced, for both their benefit and that of future generations. The construction industry is beginning to adopt the concept of sustainability in all construction activities and has a significant opportunity to mitigate environmental problems associated with construction activities while contributing to a high quality of life for its clients (Pearce, Ahn, & HanmiGlobal, 2012).

The use of slag definitely contributes to environmental sustainability directly, and also to economic sustainability and social sustainability indirectly.

Recycled material and slags, along with others such as pulverized rubber tires, recycled concrete, and recycled coal fly ash, and other postindustrial recycled materials that serve as additives for construction applications can provide both technical benefit and economic and environmental benefit.

1.3 Outline of the book

There are 15 chapters in this book. Chapter 1 provides a general overview of slag utilization, and the outline of the entire book.

Chapter 2 provides general knowledge of iron and steel production, molten blast furnace slag, and steel slag produced simultaneously with iron and steel manufacturing. Chemical, mineral, physical, and mechanical properties of iron and steel slag are included in this chapter.

Chapter 3 focuses on nonferrous slags formation in the pyrometallurgical production of copper, nickel, lead, zinc, and tin. Properties of each slag type are presented in this chapter.

Chapter 4 deals with nonmetallurgical slags including phosphorus slag from element phosphorus production, boiler slag from coal combustion, and municipal solid waste incinerator slag from incineration of municipal solid wastes that have demonstrated and potential uses in civil infrastructure construction. The formation of each slag type and their distinct properties are discussed in this chapter.

Chapter 5 outlines the methods used in processing of slag, from molten stage (pretreatment) to product (posttreatment). The intrinsic properties of slag and its evaluation are also discussed.

Chapter 6 enunciates the philosophy and methodology that should be followed for slag research and its extensive use in civil infrastructure construction. Innovative thinking for slag use is introduced including blending use (co-use) with other byproducts or nontraditional materials.

Chapter 7 reviews relevant policies and regulations related to recycled material utilization and evaluation of the potential environmental impacts of slag use in construction. Project examples are also presented that related to environmental evaluation and testing.

Chapter 8 focuses on the utilization of slag as an unbound material. First, the basic technical requirements for unbound granular materials and end products are discussed; then the practical uses for slag as an unbound material, and recent research development are presented and discussed.

Chapter 9 enunciates the nature of volumetric instability of steel slag and deduction of the usability criteria for expansive slag use in nonconstrained conditions. Usability criteria presented in this chapter can be extended to other types of slags when volume stability may be questionable.

Chapter 10 focuses on the basic technical requirements for aggregate for hot-mix asphalt and various surface treatment, and pavement. Performance requirements of asphalt pavement surface are presented. Experience of the use of slag in asphalt mixes and recent research development are also presented.

Chapter 11 reviews the research development and experience of the use of slag in concrete. In this chapter, laboratory experimental data in macro- and microlevel are presented and discussed. The contribution by the intrinsic nature of steel slag to concrete strength is discussed.

Chapter 12 presents the deductions and establishment of the usability criteria for slag use in rigid matrices. This chapter discusses two new test methods developed and used in measuring slag volumetric stability, how to use the testing data in the theoretical deduction of the bulk expansion force of mass slag sample, and expansion force of single slag particle.

Chapter 13 deals with the hydraulic properties of slags of different kinds, and their use in cement manufacture. The ordinary Portland cement manufacture and requirements are also presented. The use of slag in other cementitious applications is also discussed.

Chapter 14 provides three case studies concerning steel slag and nickel slag use in highway construction and foundation construction in Greece, Saudi Arabia, and the Dominican Republic. From these construction projects, large amounts of slag materials are used.

Chapter 15 discusses how to convert inhibiting factors to positive drivers to promote the comprehensive utilization of slag; the strategies that can be used to commercialize slag as a nontraditional construction material in civil infrastructure construction.

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Ferrous metal production and ferrous slags

2

2.1 Introduction

Ferrous, which is different from ferric in chemistry, means iron related, especially iron with a valance of 2 (Fe^{++}) that exists as oxidation state (FeO). Ferrous metals, in general, refer to iron and steel materials. Steel is the major ferrous metal, an alloy of iron and carbon, and is widely used in construction and other applications. Modern steelmaking is an integrated process consisting of blast furnace (BF) ironmaking and basic oxygen furnace (BOF) or electric arc furnace (EAF) steelmaking. Molten steel from BOF or EAF process can undergo a secondary refining process in a ladle furnace, or be sent directly to the continuous caster. During ironmaking, when smelting ore, iron scrap, coke, and flux, BF slag is formed and subsequently discharged. Steel slag is formed and discharged when smelting iron, steel scrap, and flux during the steelmaking process. After molten slag is discharged, being air-cooled, or treated under different cooling regimes and processed, slag products for various applications can be produced. Fig. 2.1 is a flow chart to present the iron- and steelmaking processes and the types of slag generated from each stage.

As indicated in Fig. 2.1, the raw materials used in the BF-BOF system include iron ore, coal, fluxes (mainly limestone and dolomite), recycled steel scraps, and alloys. On average, this process uses approximately 1400 kg (3086 lb) of iron ore, 800 kg (1764 lb) of coal, 300 kg (661 lb) of flux, and 120 kg (265 lb) of recycled steel to produce 1000 kg (2205 lb) of crude steel. The EAF process uses primarily recycled steel scraps and electricity. On average, the recycled steel-EAF process uses 800 kg (1764 lb) of recycled steel, 16 kg (35 lb) of coal, and 64 kg (141 lb) of flux to produce 1000 kg (2205 lb) of crude steel (World Steel Association, 2014). To make final steel products, other materials may be used, which include manganese, silicon, nickel, chromium zinc, tin, and tungsten.

Unlike manufactured engineering materials, which are produced under quality control required by technical specifications and supplied on demand, ferrous slag is produced as a coproduct simultaneously with iron- and steelmaking and is generated daily. A considerable amount of ferrous slag is produced each year in the world. As the amount of slag tapped from the furnaces is not normally routinely measured and not all of the ferrous slag formed is tapped during a heat, the ferrous slag output levels are normally broadly estimated based on the typical slag to metal production ratios, which in turn are related to the chemistry of the raw materials to the furnaces. For typical high iron ore grades (60–66% iron), a BF normally produces approximately 0.25–0.30 tonne (0.28–0.33 ton) of slag per tonne (ton) of crude iron produced. For lower grade ores, the slag output will be higher, in some cases as much as 1.0–1.2 tonne (1.1–1.32 ton) slag per tonne (ton) of crude iron (USGS, 2013).

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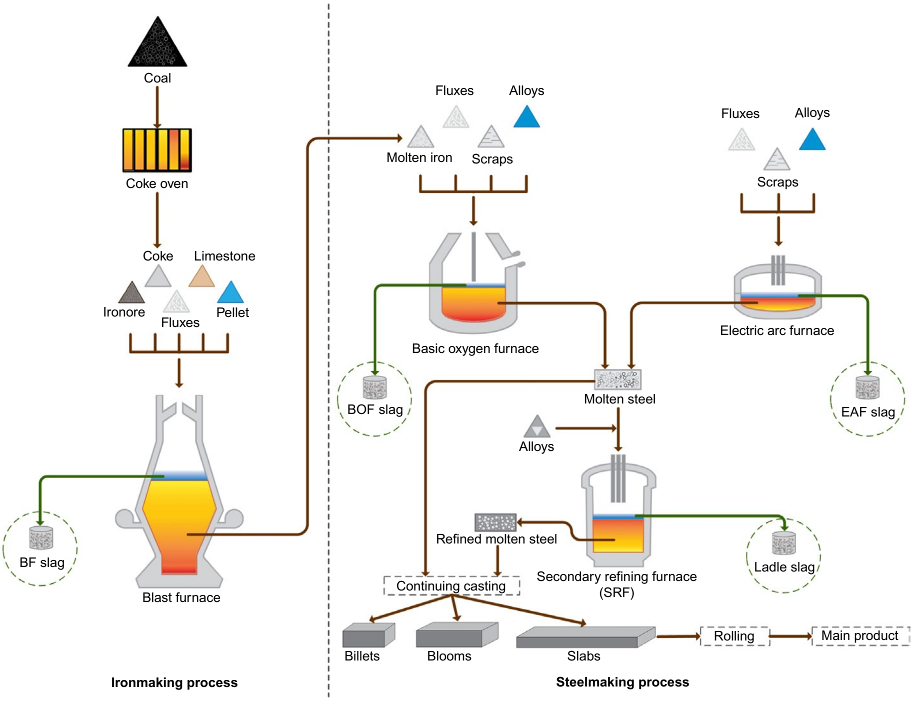

Fig. 2.1 The integrated iron- and steelmaking process and ferrous slag generation. Adapted from Yildirim, I. Z., & Prezzi, M. (2011). Chemical, mineralogical, and morphological properties of steel slag. *Advances in Civil Engineering*. http://dx.doi.org/10.1155/2011/463638.

Steel furnaces typically produce approximately 0.2 tonne (0.22 ton) of slag per tonne (ton) of crude steel. However, up to 50% of this slag is entrained metal, most of which is recovered during slag processing and returned to the furnaces. The amount of marketable steel slag after processing entrained metal is usually between 10% and 15% of the crude steel output (USGS, 2014).

On the other hand, steel will continue to be the most commonly used structural and functional materials in terms of quantity in the future. From 2012 to 2013, the world crude steel production increased by 4.0%. The output of crude steel had increased from approximately 200 million tonnes (220 million tons) in 1950 to 1600 million tonnes (1760 million tons) in 2013 (World Steel Association, 2014). Based on the slag to metal production ratios and the ferrous metal production, the estimated ferrous slag generated in the world in 2013 was approximately 600 million tonnes (660 million tons), which includes 408 million tonnes (449 million tons) of BF slag and 193 million tonnes (212 million tons) of steel slag. Iron BF slag and steel slag make up the largest portion of the slag family, which includes nonferrous slag and nonmetallurgical slag.

In terms of the properties, solidified ferrous slag is a nonmetallic and energy-containing by-product and possesses some chemical, physical, and mechanical properties that match or are similar to those of some natural or manufactured engineering materials. In addition, due to some special characteristics of ferrous slag, there exists the possibility of altering or modifying physical and chemical properties of the conventional engineering materials to produce special construction materials that can be utilized for special applications. With increasing concern about sustainable development, greenhouse emissions, and emphasis on materials reduction, reuse, and recycling, it is critical that the full potential of the use of ferrous slag is developed to reduce potential environmental impacts and for natural resources sustainability, with financial return, rather than disposal costs. Processed BF, BOF, and EAF slags are being considered to be conventional or nontraditional construction materials. The availability and properties of ferrous slag open avenues for potential engineering utilizations, and also bring scientific, technical, and managerial challenges to people in developing various optimal applications.

2.2 Ironmaking process and BF slag formation

Ironmaking is to convert iron ore or other iron-bearing materials into a form that can be easily transformed into steel. This is done primarily in a BF with other auxiliary facilities to smelt the raw materials, *burden*, to make crude iron that contains high carbon content of approximately 4–5%. This high carbon content makes iron very hard but brittle and limits its use. Steelmaking furnaces are used to make different types of steel that contain lower carbon content, usually less than 1%, and alloys.

2.2.1 Overview of ironmaking

The raw materials charged to a BF consist of iron ore, coke, fluxing stone, hot air, and water for cooling purpose. Mining iron ore or other iron-bearing materials from the ground is the first step to make iron and steel. Iron ores are rocks from which metallic iron can be economically extracted. These rocks are usually found in the form of hematite (Fe_2O_3) or magnetite (Fe_3O_4). Common types of iron ores and their iron contents are shown in Table 2.1. Six major countries in iron ore mine production from 2010 to 2013 are China, Australia, Brazil, India, Russia, and Ukraine. In the United States, in 2013, Michigan and Minnesota produced 99% of the usable iron ore in 11 iron ore mines with 9 concentration plants and 9 pelletizing plants. The United States was estimated to have produced and consumed 2% of the world's iron ore output (USGS, 2014). In BF ironmaking, iron ore accounts for approximately 70% of the total raw materials.

Table 2.1 **Common types of iron ores and their approximate iron contents**

Iron ore	Hematite	Magnetite	Siderite	Pyrite	Limonite	Taconite	Jasper
Iron compound in the ore	Fe_2O_3 (~70% Fe)	Fe_3O_4 (~72% Fe)	$FeCO_3$ (~61% Fe)	FeS_2 (~46% Fe)	Fe_3O_4 (~60% Fe)	Various (>16% Fe)	Various (25–40% Fe)

Data from Brandt, D. A., & Warner, J. C. (2009). *Metallurgy fundamentals* (5th ed.). Tinley Park, IL: Goodheart-Willcox.

Coke is produced from carefully selected coal. Different grades of coal are stocked separately and blended before transfer to coke ovens. To make coke, coal is washed, crushed, and screened in a preparation tower before being stored. Blended coal is first heated in coke ovens by gas firing for approximately 18 h to produce coke. This process is known as *carbonization*. Once carbonized, the coke is pushed out of the ovens and allowed to cool. Gas, accounting for 25% of coal's volume, is released during carbonization that is extracted by the exhausters through the collectors and primary coolers, and used for fuel in the steel plant. Other by-products such as coal tar and phenol are also extracted for other uses. Coke, with few impurities and a high carbon content, is used as the fuel and reducing agent accounting for approximately 25% of the total raw materials in the BF process.

Limestone and dolomite, which are the principal carbonate rocks, are used as flux, accounting for approximately 5% of the total raw materials. Both limestone and dolomite are sedimentary rocks composed mostly of the mineral calcite ($CaCO_3$) and dolomite ($CaCO_3 \cdot MgCO_3$) respectively. Table 2.2 lists some common carbonate minerals and their physical properties.

Table 2.2 **Common carbonate minerals used for fluxes and their physical properties**

Mineral	Physical properties	Common color
Calcite ($CaCO_3$)	Hexagonal crystal system, commonly good rhombohedral cleavage. Mohs hardness: 3; specific gravity: 2.72	Colorless or white but may be other colors because of impurities
Dolomite ($CaCO_3 \cdot MgCO_3$)	Hexagonal crystal system, commonly good rhombohedral cleavage with curved faces. Mohs hardness: 3.5–4.0; specific gravity: 2.87	White or pink
Aragonite ($CaCO_3$)	Orthorhombic crystal system, Mohs hardness: 3.5–4.0; specific gravity: 2.93–2.95	Colorless, white, or yellow, but may be other colors because of impurities

Data from Freas, R. C., Hayden, J. S., & Pryor, C. A. (2006). Limestone and dolomite. *Industrial minerals and rocks, commodities, markets, and uses* (7th ed.). Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.

The size of limestone and dolomite used in BF is 25–75 mm (1–3 in.). They can be mixed with iron ore to make agglomerates and charged to the furnaces as fluxed pellets or fluxed sinter. Agglomerates are large particles formed from finer ones, which are either fused at high temperature (sinter) or bonded at low temperatures to form a material that is handled easily and transported with minimal degradation. Limestone and dolomite are proportioned to the silica and alumina. The ratio is expressed as the basicity. For fluxed pellets, the basicity is calculated as the CaO/SiO_2 and MgO/SiO_2 ratios, which reflect only the major components (Kokal, 2006).

To make fluxed sinter, fine-sized ore is first mixed with coke and fluxes, and heated in a sinter plant. Sinter process agglomerate iron ore, dust, or fines with other fine materials at high temperature to create a product that can be used in the BF. This process has a continuous moving belt on which the coke is ignited. The high temperatures fuse the ore particles and fluxes together to form a porous clinker called *sinter*. The sintering process, which has become an important part of the overall ironmaking process, was initially developed because of iron ore in dust form. Using sinter reduces waste and makes the ironmaking process more efficient (UK Steel, 2014), and lessens the amount of raw fluxing stone required in the process.

The amount of flux charged directly to the BF varies widely depending on the amount charged in fluxed agglomerates. The majority of BFs operating with fluxed pellets and/or fluxed sinter require an additional amount of flux of 10–50 kg/t (20–100 lb/ton) of hot metal. Those not using any fluxed burden materials are charging 100–250 kg/t (200–500 lb/ton) of hot metal. Typically, 225–275 kg/t (450–550 lb/ton) is normal, not many modern furnaces approach 200 kg/t (400 lb/ton) (AISI, 1989).

The iron BF is a large steel cylinder up to 30 m (98 ft) high. The maximum diameter, the hearth at the bottom, is typically 9 m (30 ft). The furnace is lined with refractory firebricks, which are water-cooled, and can withstand up to 2000°C (3632°F) temperature. An iron BF can operate more or less for 15 years at pressures up to five atmospheres, and internal temperatures in excess of 1750°C (3182°F), and produce as much as 10,000 tonnes (11,000 tons) of molten iron per day and up to 50 million tonnes (55 million tons) over its service life before the heat-resistant brick lining begins to deteriorate, and then is relined. Fig. 2.2 presents a schematized BF.

An important feature of ironmaking is that the process is continuous. First, coke, iron ore, and sinter are charged into the top of the BF, together with flux. A hot air blast, from which the furnace gets its name, of approximate 1000°C (1832°F), is injected through nozzles, called *tuyeres*, from the base of the furnace. The air injected ignites coke and eventually supplies enough heat to melt the burden. The materials move down through the furnace and are heated from below. The blast air may be oxygen enriched, and coal or oil is sometimes also injected to provide additional heat and reduce coke requirements. The blast fans the heat in the furnace to white-hot intensity, and the iron in the ore and sinter is melted out to form a pool of molten metal in the bottom, or *hearth*, of the furnace. The slag results from fusion of the fluxing stone (limestone and dolomite) together with the gangue (siliceous and aluminous residues from the iron ore) and coke ash in the BF. The molten slag, which is lighter than the metal, floats on top of the molten iron and below the unmelted burden. Both molten materials are drawn off at regular intervals from the continuous process furnace. Because the raw materials are carefully controlled to produce consistent crude iron, the range of slag chemical composition is fairly narrow for a specific ore and furnace operation. The hot air blast to the furnace burns the coke and maintains the very high temperatures that are needed to reduce the ore to iron. The reaction between air and the fuel generates carbon monoxide. This gas reduces the iron oxide, with a valance of 3, in the ore to iron.

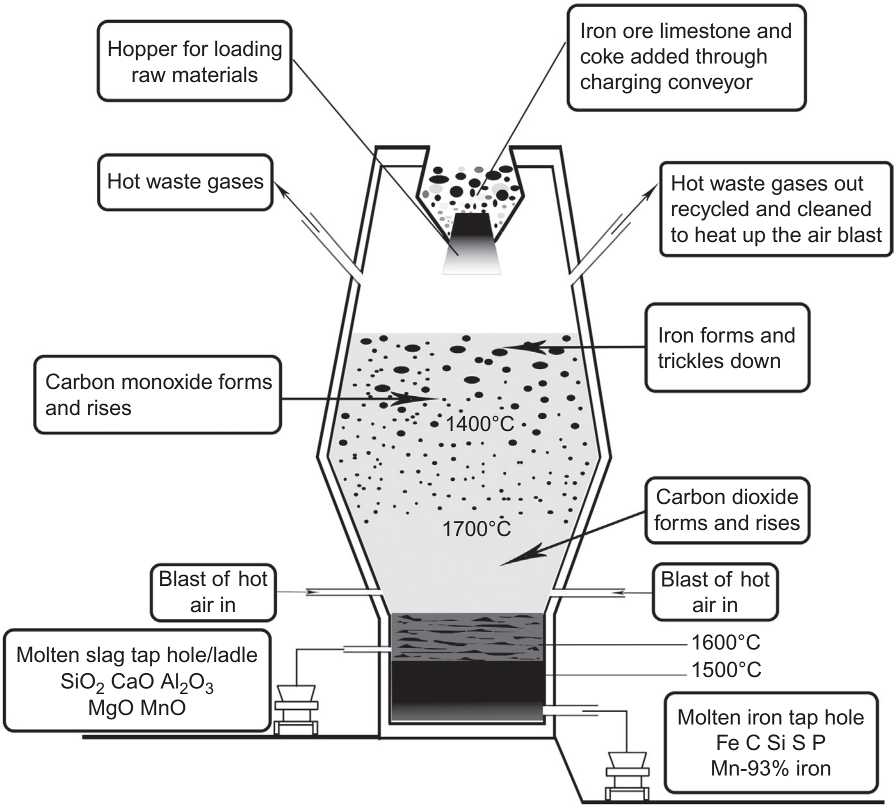

Fig. 2.2 Schematized iron BF.

The main chemical reactions (reduction) in molten iron production are

$$Fe_2O_3(s) + 3CO(g) \rightarrow 2Fe(l) + 3CO_2(g)$$
$$Fe_2O_3(s) + 3H_2(g) \rightarrow 2Fe(l) + 3H_2O(g)$$

The hot gas, which contains a lot of carbon monoxide and leaves the furnace, is collected and cleaned and reused as a fuel for other steelmaking processes or to heat up the air blast to the furnace.

When a sufficient quantity of molten iron accumulates in the hearth of the BF, it is tapped off into ladles for steelmaking. As slag builds up on the surface of the molten iron, it is tapped off at regular intervals through a separate notch or taphole. Meanwhile, the raw materials continue to be charged into the top of the furnace, and heated air is blasted in at the bottom. This process goes on throughout the lifetime of the furnace.

2.2.2 BF slag formation

In iron- and steelmaking, flux has two major functions: (i) to make the impurities in the raw materials more easily fusible; (ii) to furnish a substance with which some impurities may combine in preference to the metal. Fluxing practice, including the type and chemical composition of fluxing stone, proportion, particle size, and the way it is added may affect the formation and properties of the slag. As discussed in Section 2.2.1, limestone and dolomite, which are the major basic fluxes used in iron- and steelmaking, supply lime (CaO) and magnesia (MgO), respectively, in smelting iron ores to form slag with acid components silica (SiO_2) and alumina (Al_2O_3). The ideal flux is low in acids, such as silica, alumina, sulfur, and phosphorus. Typical chemical analyses for limestone, dolomite, and their respective calcined products are shown in Table 2.3. In nature, iron ores are found in impure states, often oxidized and mixed in with silicates of other metals. During smelting, when the ore is exposed to high temperatures, the impurities are separated from the molten metal, combined with the basic oxides in the fluxes to form compounds in the $CaO–SiO_2–MgO–Al_2O_3$ system, and removed. In many smelting processes, oxides are introduced to control the slag chemistry, assisting in the removal of impurities and protecting the furnace refractory lining from excessive wear. In this case, the slag is termed *synthetic*.

Table 2.3 Major chemical compositions of limestone, dolomite, and burnt lime

Component	Limestone	Dolomite	Burnt lime	
			High-calcium	**Dolomitic**
$CaCO_3$	95.3	54.5	–	–
$MgCO_3$	3.1	42.0	–	–
CaO	53.4	30.6	88.5	56.0
MgO	1.5	20.1	2.5	36.8
SiO_2	0.7	2.6	1.2	4.7
R_2O_3[a]	0.3	0.3	0.5	0.5

[a] $Fe_2O_3 + Al_2O_3 + Cr_2O_3 + TiO_2$.

Data from Kokal, H. R. (2006). Fluxes for metallurgy. *Industrial minerals and rocks, commodities, markets, and uses* (7th ed.). Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.

2.2.2.1 Slag formation

In the BF, calcination of limestone begins at temperatures higher than 800°C (1472°F) and dolomite typically begins dissociating at about 700°C (1292°F) (Ricketts, 1992). The melting point of pure lime is higher than process temperatures during smelting of iron ores. However, when lime is added to other components, such as silica, the melting point is lowered and a liquid phase forms. The major chemical reactions of calcination are

$$CaCO_3 \rightarrow CaO + CO_2 \ (\text{for pure calcium carbonate})$$
$$MgCO_3 \rightarrow CaO + CO_2 \ (\text{for pure magnesium carbonate})$$

These are endothermic reactions, which absorb heat from the furnace. It is important to control the addition of limestone because too much limestone would lower the temperature in the furnace.

Calcium oxide is base and reacts with acidic impurities in the iron ore and other raw materials forming molten BF slag. The liquid slag also absorbs much of the sulfur existing in the various raw materials (Rayner-Canham & Overton, 2006). Calcium oxide reacts with silicon dioxide to produce calcium silicate:

$$\mathrm{CaO} + \mathrm{SiO_2} \rightarrow \mathrm{CaSiO_3}$$

Iron BF slag is controlled to maintain a composition with about 10% Al_2O_3 to achieve a relatively constant melting point and to maintain slag liquid over a wide range of lime and silica combinations. The melting point is typically 1400–1500°C (2552–2732°F). Ferrous iron reacts with silica at much lower temperatures than calcium and alumina, and local melting can occur in the lower part of a BF shaft. One purpose of flux in fluxed pellets is to avoid early melting that results from the formation of iron silicate (Fe_2SiO_4 or fayalite) by preferentially reacting silica in the pellets with lime and magnesia (Ranade, 1992).

2.2.2.2 Flux proportion

The selection of fluxes is governed by well-established physical and chemical laws that apply at smelting temperatures. Once selected, limestone and dolomite are proportioned to the silica and alumina in producing agglomerates. The ratio is expressed as the basicity (Ranade, 1992). Basicity is the ratio of basic oxide components to acid oxide component(s) in the slag and is defined in several ways. Because lime and silica are the most prevalent components in basic slags, the definition of basicity is often given as the lime-to-silica ratio or binary basicity (B_2)

$$B_2 = \mathrm{CaO} / \mathrm{SiO_2}$$

where the weight percent of the chemical components is used to compute the ratio. This ratio is also called the C/S ratio in the manufacture of fluxes pellets. The magnesia-to-silica ratio (M/S ratio) is also specified for fluxed pellets.

The commonly used definition of basicity in BF practice is the four-component basicity (B_4), or total basicity, defined as

$$B_\mathrm{T} = B_4 = \left(\mathrm{CaO} + \mathrm{MgO}\right) / \left(\mathrm{SiO_2} + \mathrm{Al_2O_3}\right)$$

Total basicity sometimes is modified to include titania or phosphorus (P_2O_5) as acids (Kokal, 2006). To achieve a fluid slag with adequate capacity to remove sulfides, total basicity (B_T) of iron BF slag is typically between 1.05 and 1.15 (AISI, 1989).

2.2.2.3 Particle size

Traditionally the size of fluxing stone directly charged into an iron BF was approximately 150 mm (6 in.). Nowadays, the size is as fine as 50 × 12.5 mm (2 × 0.5 in.) to make them compatible with other raw materials. The smaller particle size will help form complete reactions among the compounds in the BF.

2.2.2.4 Viscosity

Viscosity of liquid slag is another factor to consider for flux additions. Silica can form complex networks in the molten sate. These networks comprise chains of silica molecules that result in very viscous flow conditions. Because silica also melts at a high temperature, separation and movement of silica is difficult. The addition of high-calcium lime breaks up the silicate networks, lowers the melting point, and decreases viscosity and is used to minimize the variability of viscosity over a range of slags compositions. However, if sufficient lime is present to precipitate dicalcium silicate (a solid phase), viscosity will increase rapidly (Kokal, 2006).

2.3 Basic properties of BF slag

The chemical and mineral compositions and basic physical properties of solidified BF slag have been well defined by researchers. BF slag is defined by the American Society for Testing and Materials (ASTM) as the nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases that is developed in a molten condition simultaneously with iron in a BF (ASTM, 2009). Air-cooled BF slag is permitted to solidify under the prevailing atmospheric conditions, either in a pit adjacent to the furnace or in one some distance away to which it is transported in large ladles. After solidification, the cooling may be accelerated by water sprays that produce cracking and facilitate digging of the slag.

2.3.1 Chemical and mineral compositions

2.3.1.1 Chemical composition

The full range of chemical composition of BF slag based on the analyses of over 100 sources from different countries is summarized in Table 2.4. The overall chemical composition can vary over a wide range from different operations depending on the nature of the ore, the chemical composition of the fluxes, the coke consumption, and the type of iron used. It can also change over the years with alterations in the sources and types of ore being smelted. These variations affect the relative contents of the four major constituents (lime, silica, alumina, and magnesia) and also the amounts of the minor constituents (sulfur in the form of sulfide, and ferrous and manganese oxides). However, it is noted that the chemical composition of BF slag from one plant can be within a relatively narrow range. Hewlett (1998) provided the chemical composition of BF slag samples from the United Kingdom, Canada, France, Germany, Japan, Russian, South Africa, and the United States, indicating that CaO ranged from 34% to 43%, SiO_2 from 33% to 37%, Al_2O_3 from 8% to 16%, MgO from 5% to 14%, Fe_2O_3 from 0.3% to 2.0%, MnO from 0.5% to 1.1%, and SO_3 from 0.9% to 2.0%.

Hewlett (1998) also stated that in general the lime content in BF slag may range from 30% to 50%, silica 28% to 38%, alumina 8% to 24%, magnesia 1% to 18%, sulfur 1% to 2.5%, and ferrous and manganese oxides 1% to 3%, except in the special

Table 2.4 **Full range of chemical composition of BF slag**

Component	Composition range (%)	Component	Composition range (%)
Lime (CaO)	31–50	Iron (FeO or Fe_2O_3)	0.3–2
Silica (SiO_2)	27–45	Manganese (MnO)	0.1–2.3
Alumina (Al_2O_3)	7–24	Sulfur (S)[a]	0.6–3
Magnesia (MgO)	1–18	P_2O_5	<0.1

[a] In the form of calcium sulfide or calcium sulfate.

Data from Dobrowolski, J. A. (Ed.), (1998). *Concrete construction handbook*. New York, NY: McGraw-Hill; Hewlett, P. C. (1998). *Lea's chemistry of cement and concrete* (4th ed.). Burlington, MA: Elsevier; Lee, A. R. (1974). *Blast furnace and steel slag*. New York, NY: John Wiley & Sons; National Slag Association (NSA). (1992). *Properties and uses of iron and steel slags. MF 182–6*. Pleasant Grove, UT: NSA; Nippon Slag Association (NSA). (2014). http://www.slg.jp/e/.

case of ferromanganese prediction when the manganese oxide content of the slag may be considerably higher. Lankford, Samways, Graven, and McGannon (1985) stated that typical iron BF slag contains 32–42% SiO_2, 7–16% Al_2O_3, 32–45% CaO, and 5–15% MgO.

2.3.1.2 Mineral composition

The conditions of cooling control both the growth of mineral crystals and the quantity and size of gas bubbles that can escape before being trapped by solidification of the slag mass. Thus, within the limits imposed by the particular chemical composition, the cooling conditions determine the crystalline structure and the density and porosity of the slag. Although BF slag contains dominantly CaO, SiO_2, MgO, and Al_2O_3, these complex interactions are customarily represented on ternary system phase equilibrium diagrams.

Research by high-temperature microscopy applied to study phase equilibria has concluded that the system CaO–SiO_2–Al_2O_3–MgO accounts for approximately 95% of slag composition (Gutt & Russell, 1977). The crystalline minerals that form BF slag are compounds of the oxides of calcium and magnesium with silica and alumina. Sulfur is also present as sulfides and polysulfides, as sulfates and thiosulfates, and as elemental sulfur in small quantities. There are also small quantities of compounds of iron and manganese, and traces of manganese, titanium, and fluorine.

The possible assemblages of minerals formed by the four major constituents CaO, SiO_2, Al_2O_3, and MgO, in the range of proportions characteristic of slag, cannot be predicted with certainty from phase equilibrium diagrams. Estimates that have been made are, however, in reasonably close agreement with the results of microscopic studies on thin sections or polished etched surfaces of slags.

The most common minerals are melilite, a name applied to any of a series of solid solutions from akermanite, which is represented by $2CaO{\cdot}MgO{\cdot}2SiO_2$ (C_2MS_2), and gehlenite $2CaO{\cdot}Al_2O_3{\cdot}SiO_2$ (C_2AS). In slags of low lime and high alumina content, the mineral anorthite $CaO{\cdot}Al_2O_3{\cdot}2SiO_2$ (CAS_2) may appear. In slag having a high lime content, the orthosilicate $2CaO{\cdot}SiO_2$ (C_2S) may be formed. This mineral is known also as *dicalcium silicate*, and is one that can cause falling, or spontaneous disintegration, when it changes its crystalline structure from β to γ form.

Slags of relatively low MgO content, up to 5%, usually contain melilite as the main constituent. Melilite is the name given to an isomorphous series of solid solutions of which the two principal end members are gehlenite (C_2AS) and akermanite (C_2MS_2). In some slags the solid solution may be replaced by akermanite itself. Other minerals that may occur in slags are bredigite (α′ C_2S), larnite (β C_2S), γ C_2S, pseudowollastonite and wollastonite (CS), rankinite (C_3S_2), merwinite (C_3MS_2), spinel (MA), diopside (CMS_2), monticellite (CMS), anorthite (CAS_2), and forsterite (M_2S). The only one of these minerals that is active and will hydrate is dicalcium silicate in the α′ or β form; the γ form is inert. Periclase (MgO) has only been observed in slags of high MgO content exceeding 16% when remelted and heat treated. Theoretically it can occur in the assemblages. Hewlett (1998) provided mineral analyses based on 21 BF slag samples and summarized the results as in Table 2.5.

Some of the minerals can appear in more than one form. Thus both pseudowollaston and wollastone (the high- and low-temperature forms of CS) may be observed, but the former is the more common. C_2S may also appear in more than one form. The higher-temperature forms observed are α′ or β into which α′ may transform on cooling. Falling slags contain the γ form often mixed with β.

In addition to the above minerals, all BF slags contain calcium sulfide, occasionally in the form of well-shaped but small crystals, but more often having the appearance of a noncrystalline or dendritic mass. Other minor constituents such as alkalies or iron and manganese oxides, when present in small amounts, of the order of 1%, probably occur in solid solution in one of the other minerals. At higher contents, of the order of 3%, they may, however, occur as sulfides (Hewlett, 1998).

2.3.1.3 Dicalcium silicate

The compound dicalcium silicate occurs in four different crystalline forms, known as α, α′, β, and γ forms. The α′ form occurs at temperature above 1420°C (2588°F), when the slag is in the liquid state. When the temperature falls to about 675°C (1247°F), the dicalcium silicate occurs in the β form. When dicalcium silicate changes from the β to γ form, which it can do at ambient temperatures, it increases in volume by about 10%, and if the silicate is in sufficient quantity this expansion will cause disintegration of the slag matrix. However, studies have shown that dicalcium silicate cannot form in significant amounts when the ratio of the lime and magnesia to the silica and alumina and sulfur is kept within the limits given by either of the formulae

$$\mathrm{CaO} + 0.8\mathrm{MgO} \le 1.2\mathrm{SiO_2} + 0.4\mathrm{Al_2O_3} + 1.75\mathrm{S}$$
$$\mathrm{CaO} \le 0.9\mathrm{SiO_2} + 0.6\mathrm{Al_2O_3} + 1.75\mathrm{S}$$

If slag contains partially reduced iron oxides, the oxidation of such constituents leads to expansion that may cause disintegration of the slag. Such instances are rare, but a simple water-immersion test easily detects the expansion (Lee, 1974).

Table 2.5 Some possible minerals from the four-component system in air-cooled BF slag

Number of samples of 21 examined	C_2AS/C_2MS_2 solid solution	C_2MS_2	C_2S	CS	C_3S_2	C_3MS_2	MA	CMS_2	CMS	CAS_2	M_2S	MgO
5	X		X		X							
5	X			X						X		
4	X			X	X							
3	X					X	X					
2	X						X			X		
1		X					X			X	X	
1		X				X	X		X			

Data from Hewlett, P. C. (1998). *Lea's chemistry of cement and concrete* (4th ed.). Burlington, MA: Elsevier.

2.3.2 Basic physical properties

An air-cooled BF is predominantly crystalline in nature, with a cellular or vesicular structure resulting from bubbles of gases that were dissolved in the molten slag. The air-cooled slag crushes to angular, roughly cubical particles with pitted surfaces. Excellent bond is provided with either hydraulic cements or bituminous binder materials. High internal friction angles and particle interlock provide excellent stability. Bulk density is dependent upon grading and particle size; the larger particles contain more internal cells or vesicles and have a lower bulk density. The coarse sizes may have bulk densities as much as 20% lower than natural aggregates with the same gradation, while the fine material (passing a 4.75 mm or No. 4 sieve) is nearly equal to natural sand in density. The aggregate is highly resistant to weathering effects, and does not readily polish to produce slippery surfaces.

Air-cooled BF slag has a low coefficient of thermal expansion and a high fire resistance. It has relatively high water absorption due to its porosity. BF slag is one of the more absorbent types of aggregates. The combination of rough texture and relatively high porosity, together with its alkaline reactivity, produces good adhesion characteristics, particularly in the presence of water.

The physical properties of BF slag from any one plant are reasonably consistent, the variation that do occur being no greater than those that occur in natural rock from a quarry (Lee, 1974). The types of ore used by the plant can, however, produce larger variation in the slag than those found from one plant to another. These variations are caused by the need to adjust the burden charged to the BF to suit the type of ore being used.

The physical properties, such as density, porosity, and particle size, are affected by the cooling rates and chemical composition. Table 2.6 shows some physical properties of air-cooled BF slag.

Table 2.6 Physical properties of air-cooled BF slag

Specific density	Bulk density (kg/m^3)	Water absorption (%)	Impact value dry (%)	Crushing value (%)	Polished stone value (%)	Abrasion value (%)
2.38–2.76	1150–1440	1.5–5	21–42	25–39	50–63	5–31

Data from Lee, A. R. (1974). *Blast furnace and steel slag*. New York, NY: John Wiley & Sons; Dunster, A. M. (2002). Blastfurnace slag and steel slag as aggregate: A review of their uses and applications in UK construction. *Proceedings of the 3rd European slag conference*, October 2–4, Keyworth, UK.

2.4 Steelmaking processes and steel slag formation

As seen in Fig. 2.1, crude iron is refined in a BOF or an EAF to become crude steel. It may also undergo a second refining in a ladle furnace. The BOF steelmaking process is currently the dominant steelmaking technology, which makes approximately 60% of the world's total output of crude steel. In the United States, this figure is slowly declining, from 55% in 2001 to 47% in 2006 (Stubbles, 2014). This is mainly due to the availability of recycled steel scrap, less energy consumption by the EAF process, and the grade of steel produced. However, elsewhere in the world the use of BOF is growing.

2.4.1 BOF steelmaking and slag formation

The primary raw materials for the BOF include approximately 70–80% liquid hot metal from the BF, balanced with recycled steel scrap and flux materials, which are mainly limestone, dolomite, and fluorspar (CaF_2). The quantities of steel scrap are related to factors such as silicon and carbon content and temperature of the molten iron. Pure oxygen (>99.5%) is used to help melt the raw materials.

The principal active ingredients of the limestone and dolomite are CaO and MgO. Fluxes are charged into the furnace, *vessel* or *converter*, to absorb impurities and remove phosphorus and sulfur from the molten iron. Steel slag is formed during this process, which is neutral with respect to the refractory lining of the furnace. To help prevent erosion and dissolution of magnesia brick, 5–12% magnesia is maintained in steel slag. This also aids in controlling the viscosity of steel slag (Kokal, 2006).

The amount of added fluxes usually depends on the silicon, sulfur, and phosphorus contents of the metals, and the purity of the fluxes. By decreasing the silicon content of hot metal and lowering the manganese content, the amount of lime required in steelmaking will decline. Increased use of scrap, along with external desulfurization, also results in lower flux consumption in steelmaking. There is a large number of possible grade of steel that can be produced but at the end of refining, they can be simply classified as high, medium, and low carbon grades. The lower the carbon content, the higher the oxygen level, with more iron oxide generated and usually more limestone and dolomite are needed for slag formation.

The BOF is refractory lined and is open topped to rapidly refine molten iron into steel. Basic refers to the magnesia (MgO) refractory lining, which wears through contact with hot basic slag, molten steel, and raw materials.

The capacity and dimensions of typical BOF vessel are 228 tonne (250 ton), with 10.4 m (34 ft) height, 8 m (26 ft) outside diameter, 0.9 m (3 ft) barrel lining thickness, and 227 m^3 (8000 cu ft) working volume. There are also several modifications to the BOF, such as the Q-BOP (quick-quiet basic oxygen process) and OBM (oxygen bodenblasen Maxhuette), for which the required oxygen is injected through hydrocarbon shrouded tuyeres located in the bottom of the furnace. Fig. 2.3 is a schematic illustration of a BOF.

The BOF operation, or *heat*, begins when the vessel is tilted about 45 degrees toward the charging aisle and scrap charge is dumped from a charging box into the mouth of the cylindrical BOF. The hot metal is immediately poured directly onto the scrap from a transfer ladle. The charging takes a couple of minutes. Then the vessel is rotated back to the vertical position and lime and dolomite fluxes are dropped onto the charge from overhead bins while the lance is lowered to a couple of meters (a few feet) above the bottom of the vessel. The lance is water-cooled with a multihole copper tip. Through this lance, pure oxygen is blown into the BOF at supersonic velocities.

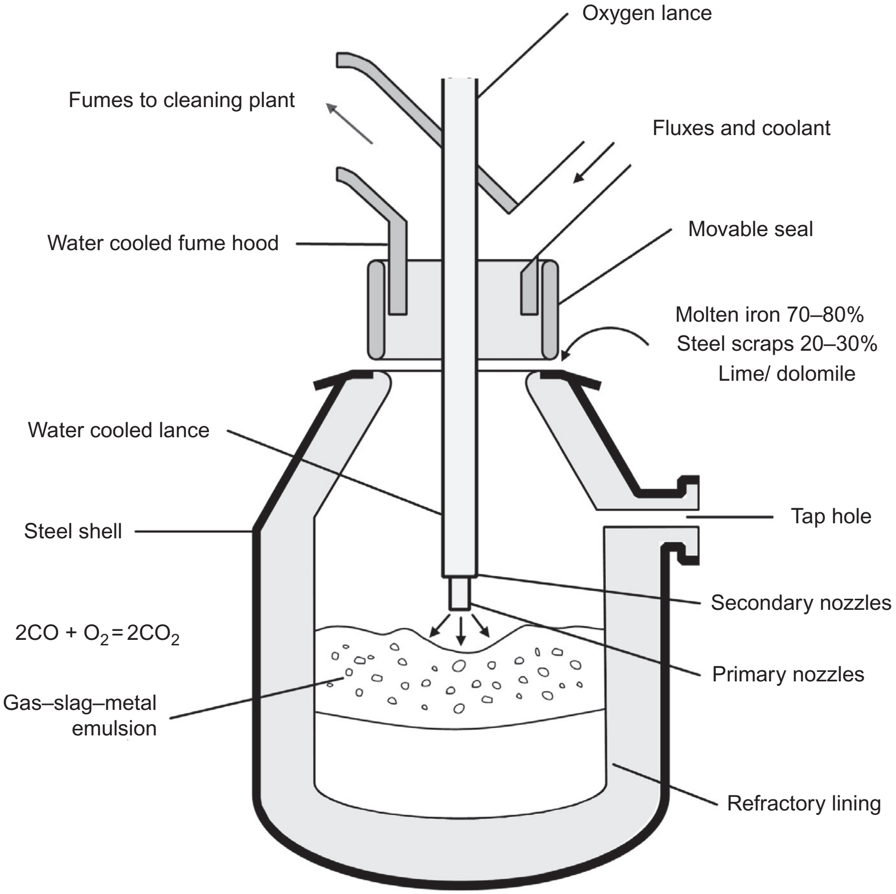

Fig. 2.3 Schematic illustration of BOF.

Heat generated by the oxygen raises the temperature inside the vessel to up to 1700°C (3092°F). This melts the scrap and lowers the carbon content in the molten iron to less than 1% and helps remove sulfur and phosphorus (Stubbles, 2014). The tap-to-tap time is approximately 40 min, and the range is approximately 30–65 min, of which 50% is "blowing time." Blowing continues for a predetermined time based on the metallic charge chemistry and specification.

Nearing the end of the blowing or "refining" cycle, after approximately 20 min, a temperature reading and a sample are taken for analysis. The specified chemical analysis is conducted at 1593–1649°C (2900–3000°F). Once the temperature and chemical composition of the hot metal are known, a computer charge model determines the optimum proportions of scrap and hot metal, flux additions, lance height, and oxygen blowing time. The lance is generally preprogrammed to move to different heights during the blowing period. If the analysis shows that everything is correct, the vessel is tilted and the steel is poured into a ladle. This process is called tapping the steel. At this time alloying elements are added to bring the steel to the required specification. From here it may undergo further refining in a secondary refining process or be sent directly to the continuous caster where it is solidified into semifinished shapes: blooms, billets, or slabs (Stubbles, 2014; Miller, Jimenez, Sharan, & Goldstein, 1998).

After tapping the steel, the molten steel slag is poured off into a slag cart and carried to the slag-treating bays for air-cooling. The basic operational steps of the BOF process are shown in Fig. 2.4.

Further treatment of the steel takes places in a ladle furnace, including such things as bubbling the steel with an inert gas (eg, nitrogen) to ensure thorough mixing of the alloying elements, injection of materials to refine impurities, and for some special steels, a vacuum degasser is used to remove dissolved gasses, particularly oxygen and hydrogen. Then the steel contains between 0.1% and 1.0% carbon.

2.4.2 EAF steelmaking and slag formation

The important feature of the EAF steelmaking process is that the raw materials are recycled steel scrap and fluxes without the step of iron ore extraction. This results in overall cost of per tonne of annual installed capacity in the range of \$127–182/t (\$140–200/ton) for an EAF-based operation compared to approximately \$1110/t (\$1000/ton) for a BF-BOF-based operation (Jones, 1988).

The EAF is cylindrical in shape. The furnace bottom consists of a spherically shaped bottom dish. The shell sitting on top of this is cylindrical and the furnace roof is a flattened sphere. Most modern furnaces are of the split shell variety. This means that the upper portion of the furnace shell can be quickly decoupled and removed from the bottom. This greatly minimizes downtime due to change out of the top shell. Once the top shell is removed, the furnace bottom can also be changed out fairly quickly. Some shops now follow a practice where the shell is changed out on a regular basis every few weeks during an 8-h downshift.

The furnace sidewall above the slag line usually consists of water-cooled panels. These panels are hung on a water-cooled cage that supports them. The furnace roof also consists of water-cooled panels. The center section of the roof that surrounds the electrode ports is called *roof delta* and is a cast section of refractory that may be water-cooled. The furnace bottom consists of a steel shell with several layers of refractory (Jones, 1988).

Steel scraps are first separated, graded, and sorted into different classes of steel in scrap yards. The scrap yard operator will prepare buckets of scrap according to the needs of the smelter. The scrap is layered in the bucket according to size and density to promote the rapid formation of molten steel in the furnace, and minimize scrap cave-ins, which can break electrodes. The charge may include lime and carbon (Yildirim & Prezzi, 2011).

EAFs are equipped with graphite electrodes and resemble giant kettles with a spout or an eccentric notch on one side. An electric current is passed through three graphite electrodes and forms an arc. The heat generated by this arc melts the scrap. The roof of an EAF can pivot and swing to facilitate the loading of raw materials. The capacity of EAFs have been developed from approximately 135 to 270 tonnes (150–300 tons) of steel per cycle.

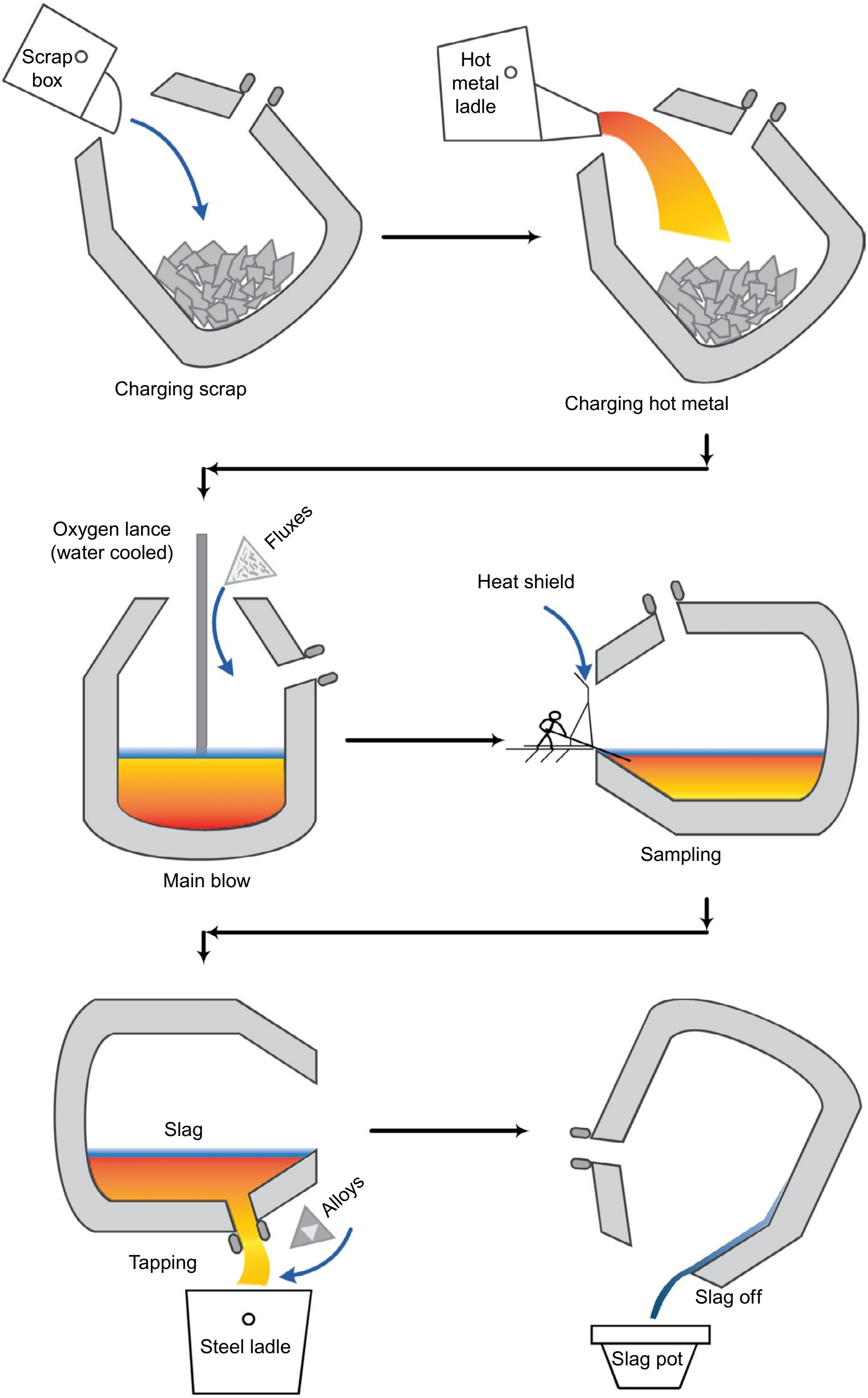

Fig. 2.4 Schematic of operational steps in BOF steelmaking.
Adapted from Miller, T. W., Jimenez, J., Sharan, A., & Goldstein, D. A. (1998). Oxygen steelmaking process. In R. J. Fruehan (Ed.), *The making, shaping, and treating of steel* (11th ed.). Pittsburgh, PA: AISE.

The EAF operation starts with the charging of various types of steel scrap to the furnace. The roof and electrodes are raised and are swung to the side of the furnace to allow the scrap-charging crane to move a full bucket of scrap into place over the furnace. Two to three buckets of scrap per heat is normal. Some operations achieve a single bucket charge. The scrap falls into the furnace and the scrap crane removes the scrap bucket. The roof and electrodes swing back into place over the furnace. The roof is lowered and then the electrodes are lowered to strike an arc on the scrap, which causes electricity to travel through the electrodes and the metal itself. The electric arc and the resistance of the metal to this flow of electricity generates the heat. This commences the melting portion of the cycle. As the scrap melts, the electrodes are driven deeper through the layers of scrap. Oxygen may also be injected through a lance to cut the scrap into smaller sizes. Usually, light scrap is placed on top of the charge to accelerate bore-in. Approximately 15% of the scrap is melted during the initial bore-in period. After a few minutes, the electrodes penetrate the scrap sufficiently so that a long arc (high voltage) tap can be used. The long arc maximizes the transfer of power to the scrap and a liquid pool of metal forms in the furnace hearth. Once the molten pool is formed, the arc becomes quite stable and the average power input increases. Calcium oxide, in the form of burnt lime or dolomite, is either introduced to the furnace together with the scrap or is blown into the furnace during melting. After several baskets of scraps have melted, the refining metallurgical operations (eg, decarburization and dephosphorization) are performed. During the steel refining period, oxygen is injected into the molten steel through an oxygen lance. Some iron, together with other impurities in the hot metal, including aluminum, silicon, manganese, phosphorus, and carbon, are oxidized during the oxygen injections. These oxidized components combine with lime (CaO) to form slag. As the steel is refined, carbon powder is also injected through the molten slag floating on the surface of the molten steel, leading to the formation of carbon monoxide. Once the desired chemical composition of the steel is achieved, the EAF is tilted, and the molten slag is poured and carried to a slag-processing unit with ladles or slag pot carriers and steel is tapped out of the furnace into a separate ladle (Seetharaman, 2005). Modern operations aim for a tap-to-tap time of less than 60 min. Fig. 2.5 shows the schematic of an EAF and a ladle furnace.

Traditionally, EAF slag may be classified into oxidizing slag and reducing slag. Oxidizing slag is generated during the oxidation refining stage, and reducing slag is generated during reduction refining. Approximately 70 kg (170 lb) of EAF oxidizing slag and 40 kg (97 lb) of reducing slag are generated for each tonne (ton) of electric furnace steel (NSA, 2014).

2.4.3 Ladle furnace refining and ladle slag

After being tapped from the BOF or EAF, the molten steel produced by the primary processes may undergo further refining to remove additional impurities remaining within the steel, or add allying elements to obtain the required chemical composition and grade of product. This refining process is called a *secondary steelmaking operation*, *secondary refining*, or *ladle refining* because it is completed within the transfer ladle. The secondary refining process is common to produce high-grade

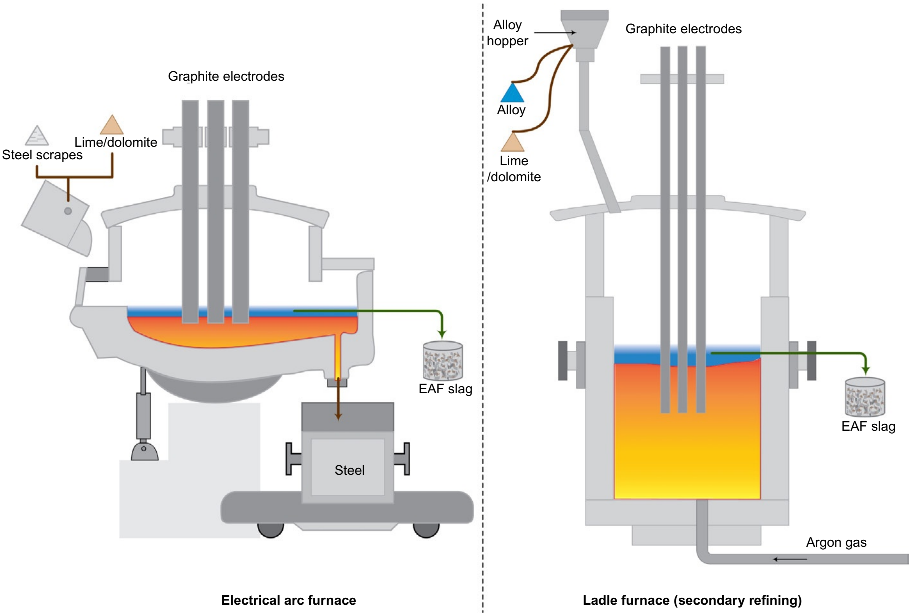

Fig. 2.5 Schematic of EAF and ladle furnace.

steel. The important functions of the secondary refining process are final desulfurization; degassing of oxygen, nitrogen, and hydrogen; removal of impurities; and final decarburization (for ultralow carbon steels). Depending on the required quality, most of the molten steel produced in BOF and EAF processes goes through some or all of the abovementioned refining processes.

Ladle furnaces look like smaller versions of EAF furnaces, having three graphite electrodes connected to an arc transformer used for heating the steel. At the bottom of the ladle furnace, typically, there is a pipeline through which argon gas can be injected for stirring and homogenizing the molten steel in the furnace. By injecting desulfurizing agents (such as Ca, Mg, CaSi, CaC_2) through a lance, the sulfur concentration in the steel can be lowered to 0.0002%. The addition of silicon and aluminum during deoxidation forms silica (SiO_2) and alumina (Al_2O_3). These oxides are later absorbed by the slag generated by the refining process. In addition, to adjust precisely the chemical composition of the steel to produce different grades of steel, the desired alloying elements are added to the molten steel through an alloy hopper that is connected to the ladle furnace. Ladle furnaces also function as a storage unit for the steel before the initiation of casting operations (Shi, 2004; Yildirim & Prezzi, 2011).

During ladle refining, slag is generated by adding fluxes to the ladle, to melt and combine with any carryover of furnace slag for the purpose of absorbing deoxidation products (inclusions), heat insulation, and protection of ladle refractory linings. Because the ladle refining stage usually involves the addition of different fluxes, the properties of these synthetic slags are quite different from those of the furnace slag (Jones, 2014; Shi, 2004).

2.5 Basic properties of steel slag

The chemical and physical properties of a specific steel slag, before undergoing special treating and processing, basically depend on the types of steelmaking process and the grades of steel produced. However, in general, the overall chemical and minerals compositions and physical properties of slag from BOF and EAF are similar.

2.5.1 Chemical and mineral compositions

During the steelmaking process, the temperature at the slag-forming stage is up to 1700°C (3092°F). Under this temperature, liquid reaction occurs. Liquid steel slag contains appreciable amounts of CaO, SiO_2, FeO, Fe_2O_3, MnO, MgO, and minor amounts of P_2O_5, Al_2O_3, K_2O, and Cr_2O_3. Obviously, many possible combinations of oxides are available. Studies (Mills & Keene, 1987) on the phase diagram data of steel slag show 11 ternary and quaternary systems possibly composed of CaO, SiO_2, FeO, Fe_2O_3, MnO, and MgO. These systems are CaO–Fe_xO–MgO, CaO–Fe_xO–MnO, CaO–Fe_x–SiO_2, CaO–MgO–MnO, CaO–MgO–SiO_2, CaO–MnO–SiO_2, Fe_xO–MgO–SiO_2, Fe_xO–MnO–SiO_2, MgO–MnO–SiO_2, CaO–Fe_xO–MgO–SiO_2, CaO–Fe_xO–MnO–SiO_2.

2.5.1.1 Chemical composition

Typically BOF slag contains approximately 10–20% SiO_2, 40–50% CaO, 10% MgO, 15–20% iron (mixed oxides), 2–5% Al_2O_3, 10% manganese oxide (MnO), and other oxides. Iron oxides content depends on carbon levels attained in the metal; it generally increases with lower carbon levels. For EAF slag, an oxidizing slag may contain 40–50% CaO, 12–20% SiO_2, 5–35% iron (mixed oxides), 3–10% Al_2O_3, 2–12% MgO, and 5–15% MnO. Typical reducing slag may contain 55–70% CaO, 15–25% SiO, 1–3% Al_2O_3, 3–12% MgO, and 0.5–2% FeO and MnO (Kokal, 2006).

In the process of basic oxygen steelmaking, basicity keeps increasing due to the continuous addition of lime and the mineral composition also changes with the change of basicity. The following replacement reactions occur:

$$2\left(\mathrm{CaO}\cdot\mathrm{RO}\cdot\mathrm{SiO_2}\right)+\mathrm{CaO}=3\mathrm{CaO}\cdot\mathrm{RO}\cdot2\mathrm{SiO_2}+\mathrm{RO}$$
$$3\mathrm{CaO}\cdot\mathrm{RO}\cdot2\mathrm{SiO_2}+\mathrm{CaO}=2\left(2\mathrm{CaO}\cdot\mathrm{SiO_2}\right)+\mathrm{RO}$$
$$2\mathrm{CaO}\cdot\mathrm{SiO_2}+\mathrm{CaO}=3\mathrm{CaO}\cdot\mathrm{SiO_2}$$

The resultant products in the right-hand side are contained in solid slag. The reason for the occurrence of the replacement reactions is that the basicity of CaO is stronger than that MgO, FeO, and MnO. Therefore, if there is sufficient CaO to meet the need of the combination of acid oxides (SiO_2, Al_2O_3, P_2O_5, FeO, Fe_2O_3), solid solution of MgO·FeO·MgO (RO phase) will crystallize.

BOF slag simply falls into two categories: acid slag and basic slag. Most BOF slag belongs to the latter category. There are also different classification methods. EAF slags may be divided into oxidizing slag and reducing slag.

The basicity for steel slag, which was initially proposed by Mason (1947), has been generally adopted. Steel slag is classified on the basicity values (B) for four categories according to the following relationship:

$$B = \mathrm{CaO} / \mathrm{SiO_2} + \mathrm{P_2O_5}$$

The basicity of steel slag is classified as follows: $B = 0.9$–1.4, olivine slag; $B = 1.4$–1.6, merwinite slag; $B = 1.6$–2.4, dicalcium silicate slag; $B > 2.4$, tricalcium silicate slag.

Several other basicity definitions, with minor variations, are also proposed (Kuwayama, Mise, Yamada, & Honda, 1989) for steel slag, which are

$$B = \mathrm{CaO} + \mathrm{MgO} / \mathrm{SiO_2}$$
$$B = \mathrm{CaO} + \mathrm{Al_2O_3} + \mathrm{MgO} / \mathrm{SiO_2}$$

Chemical compositions of steel slag from different steelmaking processes are reported in some of the literature (eg, Gutt, 1977). The comparison of chemical composition for different steel slags is summarized in Table 2.7. Some steel slags contain trace amounts of V_2O_5 and TiO_5, which are not included in the table. It is noted that the Al_2O_3 and CaO contents are normally higher for ladle slag.

Table 2.7 **Full range of chemical composition of steel slags**

	Composition range (%)		
Component	**BOF slag**	**EAF slag**	**Ladle slag**
CaO	35–45	40–60	30–60
SiO_2	12–17	10–30	2–35
Al_2O_3	0.98–3.4	2–9	5–35
FeO	10–25	10–30	0–15
MgO	3–15	3–8	1–12.6
MnO	5–15	2–5	0–5
SO_3	0–0.3	0.1–0.6	0.1–1
P_2O_5	0.2–4	0–1.2	0–0.4

Data from Jones, D.E. (1988). Utilization of ground granulated slag in Australia. In: *Proceedings of concrete workshop* (pp. 307–329), SYD, Australia; Shi, C. (2004). Steel slag—Its production, processing, characteristics, and cementitious properties. *Journal of Materials in Civil Engineering*, 230–236; Wang, G.C. (1992). *The utilization of steel Slag in engineering applications*. PhD Thesis, University of Wollongong, Wollongong, NSW, Australia. Yildirim, I. Z., & Prezzi, M. (2011). Chemical, mineralogical, and morphological properties of steel slag. *Advances in Civil Engineering*. http://dx.doi.org/10.1155/2011/463638.

2.5.1.2 *Mineral composition of steel slag*

The mineral composition of steel slag is related to the forming process and chemical composition. Basic steel slag is composed of $2CaO{\cdot}SiO_2$, $3CaO{\cdot}SiO_2$ mixed-crystal of MgO, FeO, and MnO; that is, MgO·MnO·FeO, which is repressed as RO. CaO can also enter RO phase. In addition, there are also $2CaO{\cdot}Fe_2O_3$, $CaO{\cdot}Fe_2O_3$, $CaO{\cdot}RO{\cdot}SiO_2$, $3CaO{\cdot}RO{\cdot}2SiO_2$, $7CaO{\cdot}P_2O_5{\cdot}2SiO_{2,}$ and some other oxides.

2.5.1.3 *Free lime and existing form*

It is known that a certain amount of uncombined lime (unburnt or free lime) is expressed as free CaO or f-CaO. Uncombined CaO, which has a specific gravity of 3.34, can react with moisture to produce $Ca(OH)_2$, which has a specific gravity of 2.23, with a resulting volume increase of approximately 90%. This is the primary reason to make some steel slag volumetrically expensive prone.

It is traditionally considered that it is the quantity of f-CaO, rather than its existing form, that contributes to the volume expansion. However, research has found that the existing form of f-CaO plays an important role in it (Geiseler, 1996): (i) f-CaO in solid solution may cause volume expansion; (ii) finer f-CaO particles are not likely the cause of volume expansion.

Analysis has shown that there exist two types of free lime in steel slag: the pure one and the solid solution. The former is free CaO and the latter is CaO + x% FeO ($0\% < x < 10\%$ by weight). They can be distinguished in X-ray diffraction (XRD) patterns, f-CaO having $d = 2.41$ Å and f-CaO in solid solution state having $d = 2.38$ Å. Excessive f-CaO, especially in the presence of solid solution with small amounts of FeO, is the primary cause of volumetric unsoundness (Wang, 1992).

From microscopic investigation, Geiseler (1996) found that f-CaO can exist in the form of residual lime and lime precipitated during solidification and subsequent cooling. In both categories, f-CaO exists in different appearance and particle size. The residual f-CaO can be classified into grainy lime with particle size mainly between 3 and 10 μm and spongy f-CaO with particle size mainly between 6 and 50 μm. The precipitated lime can exist on C_2F grain boundaries or within C_3S crystals and has particle size usually less than 4 μm. All types of f-CaO can hydrate; however, the most significant contributor to expansion is the spongy f-CaO with grain size up to 50 μm (Fig. 2.6).

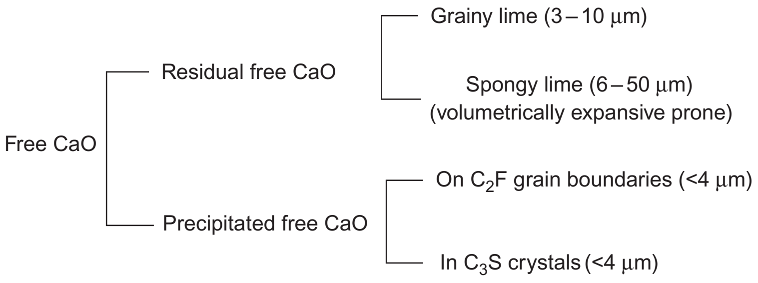

Fig. 2.6 The existing form of free lime.

2.5.1.4 *MgO and its crystalline form*

Research results show that combined magnesium oxide is not, in fact, the cause of unsoundness of steel slag. Only the free form of MgO (periclase) is expansion prone. Periclase can only be formed in the lower basicity case, whereas in the higher basicity condition, which exists in steel slag, MgO usually forms solid solution mainly with FeO and MnO (ie, RO phase).

From crystallography, it is well known that the ability of two substances to form solid solution is determined primarily by geometrical structure rather than by chemical compositions. If the radii of the substituting atoms differ by not more than about 15%, a continuous solid solution can be formed. The radii of Mg^{++}, Fe^{++}, and Mn^{++} are 0.78 Å, 0.83 Å, and 0.91 Å, respectively; therefore, they can easily form solid solution, especially in the basic liquid reaction.

Microscopic studies have shown that, in steel slag, magnesium oxide exists mainly in solid solution with FeO and MnO, so-called magnesia wüstites, while unbound MgO (periclase) is seldom found. The unbound MgO also includes the macroscopically visible fragments of undissolved refractory lining or dolomite, which were found in some slags.

Based on MgO forming solid solution, Luo (1980) proposed that the percentage ratio (stability factor) by weight of MgO to FeO plus MnO determines whether the MgO is stable or not; where, if $MgO/FeO + MnO < 1$, MgO is stable; if $MgO/FeO + MnO > 1$ MgO is unstable.

Iron mainly exists as bivalent iron (FeO), which accounts for 70% of the total iron content in steel slag (apart from electric arc slag). The ratio is less than 1 for most steel slags. The equation is based on the premise that MgO can form solid solution with FeO and MnO.

Investigations concerning the free magnesia content of steel slags have shown that good dissolution of the added dolomite in the furnace is most important. For this purpose the dolomite should be added at an early stage of the steelmaking process and grain size should be as small as possible to enable the dolomite to dissolve and react completely.

2.5.2 Basic physical properties

Compared to air-cooled BF slags, the steelmaking slags are much heavier, harder, denser, and less vesicular in nature. They have unusually high resistance to polishing and wear in pavement surface.

Solid steel slag exhibits both block shape and honeycomb shape. The former steel slag possesses luster; the latter is nonlustrous and more brittle. The specific gravity of steel slag is dependent on viscosity, surface tension of liquid steel slag and amount of dioxide contained, ferrous materials, and porosity. Moisture content of steel slag is 0.2–2.0%, specific gravity is 3.2–3.6, compressive strength is between 169 and 300 MPa (43.5 ksi), and the Mohs scale number is between 5 and 7. Grindability of steel slag is less than that of BF slag. Hardness and specific gravity are greater than those of BF slag. Like air-cooled BF slag, steel slag exhibits excellent skid-resistance properties. Some basic physical properties of steel slag are shown in Table 2.8.

Table 2.8 **Basic physical properties of steel slag**

Bulk density (kg/m^3)	Specific gravity	Crushing value	Impact value	Abrasion value	Polish stone value
1150–1440	2.38–2.76	25–39	21–42	5–31	50–63

Data from Lee, A. R. (1974). *Blast furnace and steel slag*. New York, NY: John Wiley & Sons.

2.6 Summary

Slag is generated as a by-product during iron- and steelmaking which result in considerable compositional and physical variability to various slags. However, after it is poured, the molten slag will go through special treating, handling, and processing, and various slag products can be produced with well-established quality control procedures. The current annual production of ferrous slag throughout the world is approximately 600 million tonnes (660 million tons). To correctly and successfully use a particular ferrous slag mainly depends on the understanding of its chemical, mineral, and physical properties, and the technical requirements of the end products and utilization. Processed BF slag is usually considered to be a conventional construction material. Acceptance has been growing for steel slag applications.

Depending on the cooling method, different types of slag products can be produced for different applications; for instance, air-cooled, granulated, expanded, and pelletized BF slags. The review of iron- and steelmaking processes and slag formation will form a foundation for further exploration of slag processing, utilizing, establishing usability criteria, and property measuring and testing for various utilizations.

Questions

2.1 What are the raw materials and the approximate proportion of the raw materials for ironmaking?
2.2 Describe the process of BF ironmaking.
2.3 Why does the crude iron contain such a high percentage of carbon?
2.4 How is BF slag formed?
2.5 Describe the process of BOF and EAF steelmaking.
2.6 How are BOF and EAF slag formed?
2.7 What are the differences between BOF and EAF steelmaking?
2.8 What are the functions of fluxes in ironmaking and steelmaking?
2.9 In iron BF production, what is the range of basicity of slag?
2.10 What are the main chemical and mineral compositions of BF slag?
2.11 What are the main chemical and mineral compositions of BOF and EAF steel slag?
2.12 How does the type of flux affect the chemical and mineral compositions of slag?
2.13 Can the properties of slag be modified by adjusting ironmaking and steelmaking processes?

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Nonferrous metal extraction and nonferrous slags

3

3.1 Introduction

Nonferrous metals refer to the metals that do not contain iron as their principal alloying element. Nonferrous metals, which are generally more expensive than iron and steel, are extensively used because of their desirable properties; for example, the high strength-to-weight ratio of aluminum, the high conductivity and malleability of copper, and the high resistance to corrosion of nickel and zinc. In the production of nonferrous metals, slag is generated and discharged as a by-product. A study of the production of copper, nickel, lead, zinc, tin, the slag formation, and the basic properties of the nonferrous slag is pertinent to further exploration of the utilization of nonferrous slags.

To extract a nonferrous metal from its ore, more than one step is involved. It may include calcining, roasting, smelting, converting, and refining, depending on the type of metal extracted and the purity of the ore. Being different from iron ores, most nonferrous metal ores are low grade, with metals in the forms of complex mixtures of sulfides, oxides, carbonates, and silicates. Therefore, to be economically extracted, nonferrous metal ores are normally concentrated by mineral beneficiation to separate the metal from waste rock prior to the extraction steps. Mineral beneficiation may include crushing and grinding the bulk ore to fine particles; removing any gangue (excess waste rock and minerals), liberating the mineral crystals from the ore matrix by froth flotation, and collecting metal values from the gangue.

In the extraction process, calcining is the thermal treatment of an ore to decompose an ore and eliminate volatile product, carbon dioxide or water, for instance.

Roasting is a process prior to smelting. Roasting can make chemical conversion happen by using oxygen or other elements. Also, fine ores and concentrates have to be agglomerated before they can be charged into a blast furnace, which can be completed by sinter roasting. In the roasting process, the ore is heated to a temperature below the melting point of the constituents. Sulfur and other elements, when present in the form of volatile oxides, in copper and nickel ores, for instance, are removed.

Smelting is a heating process for the production of a metal or matte. In this process, slag is formed and discharged. Generally, this process is a reduction of the metal oxide with carbon, sulfur, sulfide in a suitable furnace; for example, reverberatory, blast furnace, flash, or electric furnace. During smelting, fluxing materials are added to form a slag. The smelting process for metal extraction can be expressed as

$$\text{Mineral} + \text{gangue} + \text{reducing agent} + \text{flux} = \text{metal or matte} + \text{slag} + \text{gas}$$

The Utilization of Slag in Civil Infrastructure Construction. http://dx.doi.org/10.1016/B978-0-08-100381-7.00003-3

There are two types of smelting: reduction smelting and matte smelting. Reduction smelting is usually carried out in a blast furnace; and matte smelting in either a reverberatory furnace or a flash furnace. Both reduction smelting and matte smelting can be carried out in an electric furnace. In reduction smelting, the ore is reduced by a reducing agent (impure carbon, such as coke, along with carbon monoxide and hydrogen) combined with the roasted product, which is melted in a siliceous flux. The metal is subsequently gravimetrically separated from the composite flux, leaving the residual slag. In matte smelting, the metallic sulfide acts as a reducing agent without reducing the agent added. The products from matte smelting are molten matte and slag, not molten metal.

Converting is the next stage in smelting sulfide ore or concentrate that is in molten state. Refining is to further remove impurities from the molten metal to obtain the required property. The refined metals may not be suitable for use in a pure state, and they can be subsequently combined with other alloying elements to make the metals have the desired properties. The process for each metal may be different due to the nature of the ore and the properties of the metal. Fig. 3.1 shows the major steps of pyrometallurgy process.

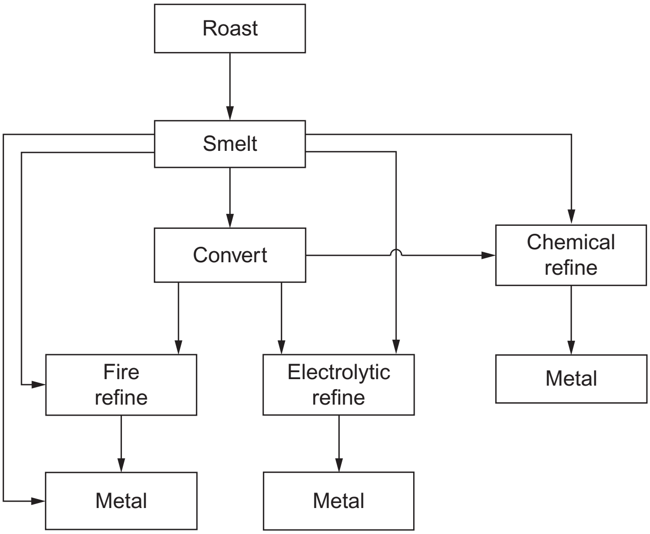

Fig. 3.1 Flow sheet of major pyrometallurgical steps in extraction of nonferrous metals.

In smelting and converting processes, flux is used. The purposes of using flux are to "absorb" the impurities in the metal-bearing materials and lower the temperature of liquid materials and the viscosity of the slag. The major fluxes in nonferrous metal production include high-grade siliceous materials, low-grade siliceous ores, and lean ores or other nearby rocks, providing that impurities are low, along with small amounts of limestone or lime (Gill, 1977). In some operations, high-grade silica rock is used. Gypsum, a sulfate of calcium, has been used as a source of lime and sulfur in nickel smelting (Habashi, 1986). The types of fluxing materials are chosen based on the chemical nature of the gangue and the desired properties of the slag, such as density and viscosity. For a siliceous gangue, a basic oxide such as lime is normally used. For a basic gangue, an acid oxide such as silica is used. Fluxes are classified as basic, acid, and neutral according to their chemical natures. In nonferrous processes flux is generally acid (silica is the primary component), although small amounts of basic flux such as limestone or lime is used to modify slag properties. Flux used in nonferrous metal extraction has similar particle size as used in iron- and steelmaking.

In nonferrous metal smelting, iron–silicate slags are formed around 1200°C (2192°F). Typical nonferrous slag contains 30–55% FeO, 30–45% SiO_2, and less than 10% CaO, although variations occur depending on the system in which the slag is formed (Kokal, 2006).

Nonferrous slags are sometimes classified as basic, acid, and neutral slag based on silicate degree. The silicate degree can be expressed as

$$\text{Silicate degree} = \frac{\text{moles of acid oxygen from } SiO_2}{\text{moles of basic oxygen from CaO, MgO, and FeO}}$$

A basic slag has a silicate degree <1 and corresponds to the composition $MO/SiO_2 > 2$, where MO is basic oxide(s). An acid slag has a silicate degree >1 and corresponds to the composition $MO/SiO_2 < 2$. A neutral slag has a silicate degree $=1$ and corresponds to the composition $MO/SiO_2 = 2$ (Ray, Sridhar, & Abraham, 2014).

As the grade of nonferrous ores is much lower than iron ore, to produce one tonne of ferrous metal, several hundred tonnes of ore have to be processed. Therefore, large quantities of "waste rocks" are generated in mining and beneficiation stages; for example, mining tailings, which are used in mining sites in tailing dam construction. The quantity of slag generated in smelting and converting stages is much less than that of the "waste rocks." However, because of the increasing production of nonferrous metals, the nonferrous slags that have to be handled cannot be underestimated.

Statistical data for the output of nonferrous slags is difficult to obtain. The difficulty mainly comes from the lack of daily records for the slag discharged, the variability of ore, raw material, the process used from one plant to another, and the slag-to-metal production ratios. For example, for copper production, the ratio of slag to metal is in the range of 0.6:1 to 1.5:1 (Kokal, 2006). For lead production, the ratio is higher.

Nevertheless, the total annual nonferrous slag production can still be broadly estimated based on the annual output of nonferrous metals and approximate production rate for nonferrous smelting facilities. The mine production of the selected five nonferrous metals in 2003 and 2013 are presented in Table 3.1. It is noted that in 2013 the output of the five nonferrous metals is 39.52 million tonnes, which has increased by 46.89% since 2003.

Table 3.1 **World mine production of five nonferrous metals in 2000 and 2013 (in 1000 tonnes)**

Year	Copper	Nickel	Lead	Zinc	Tin	Total
2003	13,900	1400	2840	8500	265	26,905
2013	17,900	2490	5400	13,500	230	39,520
Increase/decrease (%)	87.12	77.86	90.14	58.82	−13.21	46.89

Data from USGS yearbook 2014.

It is noted that in the same year, iron and steel production were 1165 and 1760 million tonnes, respectively (World Steel Association, 2014). A conservative estimation is that approximately 50 million tonnes of nonferrous slag is produced each year in the world. It is imperative to find optimum ways to minimize the disposal and utilize the nonferrous slags rationally.

3.2 Copper extraction and copper slag

Copper is one of the first metals to be used by humans and the third most extensively used metal after iron and aluminum. The percentage usage of copper and copper alloys worldwide is approximately 44% in building construction, 20% in electric and electric products, 17% in transportation equipment, 12% in consumer and general products, and 7% in industrial machinery and equipment (Brininstool, 2014).

Copper is extracted from copper ores by a pyrometallurgical (dry) method or hydrometallurgical (wet) method. The pyrometallurgical method produces approximately 80% of the primary copper (Schlesinger, King, Sole, & Davenport, 2011). Pyrometallurgical production of molten copper generates slag in the stages of smelting and converting. Many copper ores contain iron that is fluxed. Typically, silica is used to flux iron and form an iron–silicate slag. During smelting, sulfur combines with copper and some iron to form a copper–iron sulfide matte, which is separated from copper slag. The matte is converted to metallic copper by oxidation, consequently removing iron and sulfur. Copper is further refined to remove impurities. Copper alloys such as bronze and brass can be made, which contains up to 25% tin and 5–30% zinc, respectively (Brandt & Warner, 2009).

3.2.1 Copper extraction process and copper slag formation

Copper ores are found as dominantly sulfide minerals, with or without other metallic sulfides. The major copper ore is copper pyrite or chalcopyrite ($CuFeS_2$), from which a large amount of copper is obtained by smelting. Other copper ores include chalcocite (Cu_2S), malachite ($CuCO_3 \cdot Cu\ (OH)_2$), and covellite (CuS). The actual ores contain only small amount of copper. Typical copper ores contain from 0.5% Cu which is normally from open-pit mines to 1–2% Cu, which is from underground mines. Compared with iron ores, copper ores are generally too lean in copper to be smelted directly. Heating and melting the huge quantity of waste rock require prohibitive amounts of energy. Fortunately the Cu–Fe–S and Cu–S minerals in an ore can be isolated by physical means in beneficiation (concentration) into high-Cu concentrate, which can then be smelted economically (Schlesinger et al., 2011).

Normally 0.5–2.0% copper is considered satisfactory for copper extraction by concentration followed by a pyrometallurgical process that treats concentrates with 24% copper or higher, or is extracted by a hydrometallurgical process that handles lower-grade copper ores (Ray et al., 2014). Recycled scrap is becoming a source of copper production. Approximately 10–15% of scrap copper is used to produce primary copper (Schlesinger et al., 2011). Fig. 3.2 presents the major steps in the pyrometallurgical process in the extraction of copper.

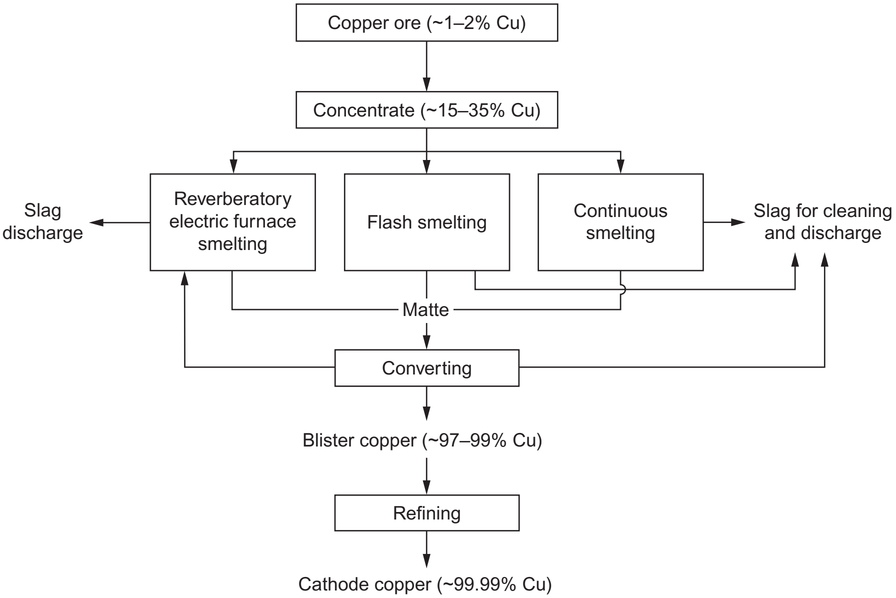

Fig. 3.2 Flow sheet of major pyrometallurgical steps in extraction of copper.

Beneficiation of copper ores comprises several steps and the methods to be used vary with the mining operations, ore characteristics, and economic aspects. Beneficiation includes crushing, screening, grinding, and sorting operations. Copper ore is first crushed and ground into very fine powder. The powder is mixed with water and chemicals so that the part of the ore containing copper (copper concentrate) floats to the surface. This process is called *froth flotation*. In froth flotation, an ore pulp is agitated and air is blown through it to produce froth. Some mineral particles, mostly sulfides, attach to their air bubbles and are concentrated in the froth, which is skimmed off from time to time. The copper is concentrated from 0.5% to 1% Cu until 24% to 30% Cu. Once obtained, the concentrate is sent to a pyrometallurgical process where the concentrate is partially roasted in order to eliminate sulfur, and later is smelted to produce a matte that contains all the material in a liquid state. The last step is to purify electrolytically the impure metal by an acid solution of copper sulfate to obtain metallic copper having a purity of 99.999% Cu.

Copper smelting can be done in a reverberatory furnace (Fig. 3.3) or a flash smelting furnace (Fig. 3.4). Flash smelting is the predominant method used today and accounts for more than 50% of the copper matte smelting in the world (Peacey, 1989). An electric arc furnace is also used along with other smelting processes.

When copper concentrate is melted in a furnace, some of the impurities are driven off to form slag. The temperature during matte smelting the sulfide concentrate is approximately 1200°C to oxidize some of the iron to generate a molten matte and slag. The products from the furnace are (i) copper matte, which is molten Cu–Fe–S

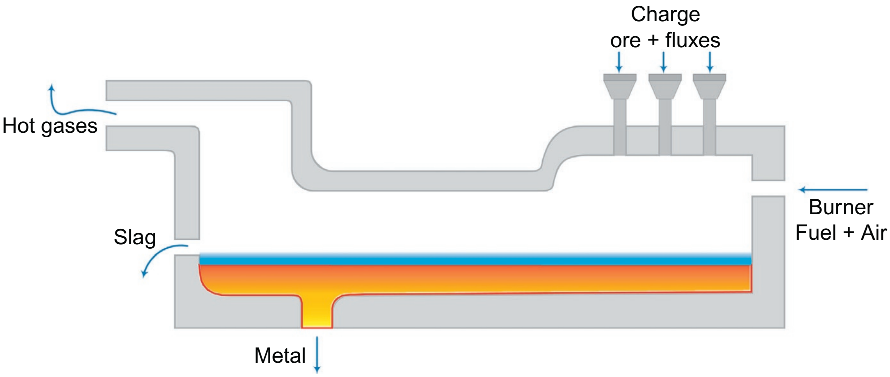

Fig. 3.3 Schematized reverberatory furnace.

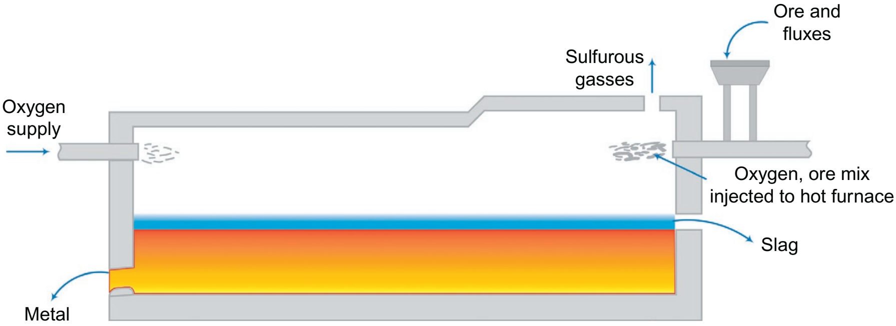

Fig. 3.4 Schematized flash smelting furnace.

matte, 45–75% Cu, which is sent to oxidation converting to molten metallic copper; (ii) molten Fe silicate slag, which is treated to recover Cu and then discarded; and (iii) SO_2-bearing off-gas:

$$CuFeS_2 + O_2 + SiO_2 \rightarrow (Cu, Fe, S)\ (\text{matte}) + FeOSiO_2\ (\text{slag}) + SO_2$$

Copper slag from matte smelting is a solution of molten oxides. These oxides consist primarily of FeO from iron oxidation, SiO_2 from flux, with small amounts of oxide impurities (eg, Al_2O_3, CaO, and MgO) from the concentrate. The oxides commonly found in copper slag include ferrous oxide (FeO), ferric oxide (Fe_2O_3), silica (SiO_2), alumina (Al_2O_3), calcia (CaO), and magnesia (MgO). This slag is often referred to as *fayalite slag* as fayalite (Fe_2SiO_4) often precipitates from the slag on cooling.

In the converting process, the matte is converted to blister copper (99% Cu) in another furnace. The products of converting are (i) molten blister copper, which is sent to fire refining and electrorefining; (ii) molten iron–silicate slag, which is sent to Cu recovery, and then discarded with or without water quenching; and (iii) SO_2-bearing off-gas.

The overall converting process may be described by schematic reaction:

Cu–Fe–S + O_2 + SiO_2 → Cu (l) + 2 FeO·SiO_2 (molten slag with some solid Fe_3O_4) + SO_2 (Schlesinger et al., 2011).

Calcium ferrite and olivine slags may occur as lime-based flux is added for two reasons: (i) copper-bearing concentrates often contain 5–10% silica and lime is added to break up silicates, take up excess silica from aluminosilicates, and reduce the viscosity of the silicarich slag (typically, 3–10% limestone or lime-bearing mix is added); and (ii) lime-based slag has a lower viscosity and a higher solubility for magnetite that has higher smelting and converting temperatures and low solubility in slag and matte may be formed in furnaces. In this case, lime-based slag separates more easily from the matte and removes arsenic, antimony, and bismuth more efficiently than siliceous slag does (Chaubal, Sohn, George, & Bailey, 1989; Turkdogan, 1983).

In converters, the particle size of flux is in the range of 6–25 mm (0.24–0.99 in.). Coarser flux is difficult to inject and to dissolve; finer flux tends to float on the bath and can be a source of dust. In some processes, smaller flux particle size may be used; for instance, the Sirosmelt process, in which limestone flux is between 5 and 10 mm (0.2–0.4 in.) in size (Kokal, 2006).

In hydrometallurgical methods, the extraction is done by acid leaching and metal precipitation. The metal copper can be precipitated from the solution by scrap iron, or by solvent extraction traded electrolytically in an acid bath. Sludge, rather than slag, is generated from hydrometallurgical process.

3.2.2 Basic properties of copper slag

Copper slag properties in reverberatory furnace smelting, flash smelting, and other processes are similar. A typical smelting slag contains approximately 30–45% FeO, 30–40% SiO_2, 5–10% Al_2O_3, 2–6% CaO, and 2–4% MgO (Kokal, 2006). Table 3.2 presents the wide-range chemical composition of copper slag from different sources. Copper slag is essentially ferrous silicate, including 2FeO·SiO_2, MgO·SiO_2, and magnetite.

Air-cooled copper slag has a dull black color and a glassy appearance. Granulated copper slag is more vesicular and porous and therefore has lower specific gravity and higher absorption than air-cooled copper slag. In general, the specific gravity of copper slag will vary with its iron content. The unit weight of copper slag is higher than that of conventional aggregate. As a general rule, the specific gravity will vary with iron content, from a low of 2.8 to as high as 3.8. The absorption of the material is typically very low. Yusof (2005) reported granulated copper slag has specific gravity of 3.4 to 3.6; bulk density of 1.76 to 1.92, and water absorption (% by mass) of 0.13. Pavéz, Rojas, Palacios, and Nazer (2004) reported that the specific gravity is higher, up to 3.98. Bulk density is between 2.24 and 2.58. Abrasion value is 18% and water absorption is 0.43.

Pozzolanic activity of granulated copper slag has been studied and the results show that granulated copper slag hydraulic activity can be used in blended cementitious materials (Mobasher, Devaguptapu, & Arino, 1996; Pavéz et al., 2004).

Table 3.2 Chemical composition of copper slag (%)

Cu	Fe (total)	Fe_3O_4	SiO_2	Al_2O_3	CaO	MgO	MnO	Cr_2O_3	S	Cl	Sb	As	Pb	Na_2O	K_2O
0.2–2.1	29–51	5.1–9.5	24–38.9	2.94–15.6	2.00–5.9	0.1–3.5	0.4–1.7	0.05	0.28–0.98	0.10	0.01	0	0.11	0.1	0.17

Data from Chesner, W. H., Collins, R. J., & MacKay, M. H. (1998). *User guidelines for waste and by-product materials in pavement construction*. FHWA-RD-97-148. Washington, DC: FHWA; Mobasher, B., Devaguptapu, R., & Arino, A. M. (1996). Effect of copper slag on the hydration of blended cementitious mixtures. *Proceedings of ASCE Materials Engineering Conference—Materials for the New Millennium*. Washington, DC, November 10–14, 1996; Pavéz, O., Rojas, F., Palacios, J., & Nazer, A. (2004). Pozzolanic activity of copper slag. *Proceedings of the VI International Conference on Clean Technologies for the Mining Industry*, Concepción-Chile, April 18–21, 2004; Scullion, T., Harris, P., & Rose-Harvey, K. (2010). *Use of copper and lead slag in highway construction: Literature search—Materials use and construction considerations*. FHWA/TX-10/0-6581-TI. Texas Department of Transportation, Austin, TX; Yusof, M. A. W. (2005). *Investigating the potential for incorporating tin slag in road pavements*. PhD Thesis, University of Nottingham, Nottingham, UK.

3.3 Nickel extraction and nickel slag

Nickel is used extensively in the steel industry to make special steel products that have resistance to corrosion, high temperature oxidation, and strong chemicals. This usage accounts for approximately 65% of total nickel output. Nickel is harder than iron, it is also used in nonferrous alloy manufacturing and specialized industries such as aerospace and nuclear reactor engineering, which accounts for approximately 20% of total nickel usage. Approximately 9% of nickel is used in plating and 6% in other uses including coins and a variety of nickel chemicals (INSG, 2014).

Primary nickel is extracted from nickel ores. However, increasingly, large tonages of recycled scrap nickel have been used to make secondary nickel or supplement newly mined nickel. Nickel occurs in nature principally as oxides, sulfides, and silicates. Nickel ores are currently mined in approximately 20 countries on all continents, and are smelted or refined in approximately 25 countries (INSG, 2014). Primary nickel is produced and used in the form of ferronickel, nickel oxides, and other chemicals, and as more or less pure nickel metal. In pyrometallurgical production of nickel, nickel slag is generated in the smelting and converting stages.

3.3.1 Nickel extraction process and nickel slag formation

Primary nickel is produced from two very different ores: sulfide ores and laterite (oxide) ores. Sulfide ores, which are generally mined from underground and often found in conjunction with copper-bearing ores, contain copper–iron sulfides in association with nickel–iron sulfides. The principal sulfide mineral of nickel is pentlandite [$(NiFe)_9S_8$]. Nickel is also found to a minor degree in violarite (Ni_2FeS_4) and pyrrhotite (Fe_7S_8). Compared with laterite ores, sulfide ores have a much lower amount of moisture, and may contain many different metals in the same ore.

Laterite ores are formed by the process of weathering and normally found in tropical regions where weathering extracts and deposits it in layers at varying depths below the ground surface. Laterite ores are excavated using large earth moving equipment and are screened to remove boulders. A typical laterite ore may contain approximately 1–1.5% Ni with 40–50% Fe existing in the form of goethite [$(FeNi)O\cdot(OH)\cdot nH_2O$]. Laterite ores contain up to 40% of free and combined moisture, which is removed in the reduction process (Ray et al., 2014).

Similar to copper extraction, nickel ores are first beneficiated to produce nickel concentrate. Then the concentrate is melted until it becomes a liquid matte, which usually contains around 45% nickel. The nickel concentrate from sulfide ores normally contains approximately 10% Ni, 2% Cu, 40% Fe, and 30% S. Various processes may be used depending on the types of ores and the smelters employed. Smelting sulfide ores can be accomplished in a reverberatory, flash, or electric smelting furnace. Modern technology uses flash smelting or electric smelting. Flash smelting is the most common process but electric smelting is used for more complex raw materials when increased flexibility is needed. Both processes use dried concentrates. Electric smelting requires a roasting step ahead of the smelter to reduce sulfur content and volatiles. Nickel matte is produced in the smelting stage. In the converting stage, flash converter or horizontal converters are used. The flow sheet presented in Fig. 3.5 shows the major pyrometallurgical steps in the extraction of nickel (Kokal, 2006).

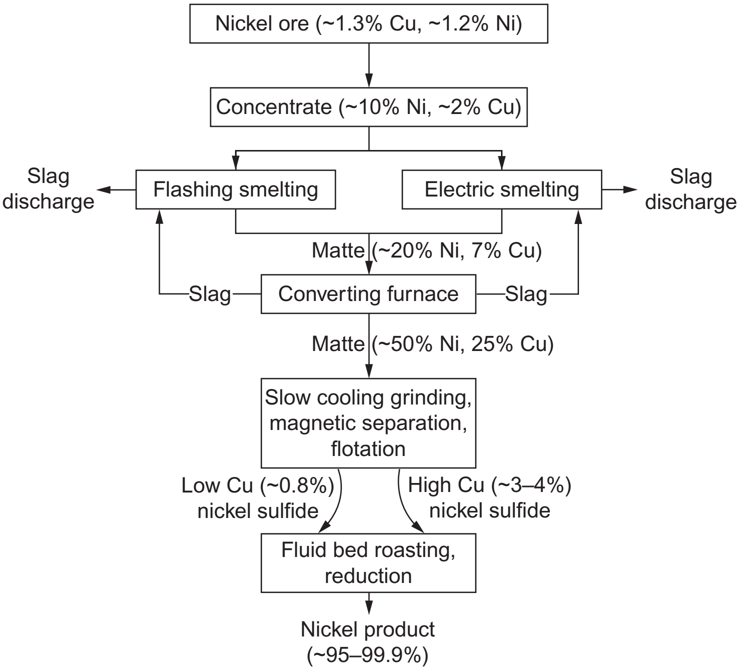

Fig. 3.5 Flow sheet of major pyrometallurgical steps in extraction of nickel.

For sulfide ore processing, nickel has to be separated from the iron present in the sulfide concentrate. This is conventionally done in both the smelting and converting stages. To aid iron rejection in the smelting stage, the concentrate is first partially roasted to oxidize the iron sulfide. This is done either in a multiple hearth roaster or in a fluid-bed roaster. During partial roasting in the temperature range 550–600°C (1022–1112°F), approximately 40% of the sulfur is oxidized and enough heat is generated to make the roasting. In a reverberatory furnace smelting, the roasted product containing the desired amount of siliceous flux is smelted to produce a matte containing the Cu and Ni values and a slag containing the gangue and oxidized iron. In flash smelting, nickel ore concentrate containing less than 1% moisture is fed to the furnace along with preheated air, oxygen-enriched air (30–40% oxygen), or pure oxygen. Iron and sulfur are oxidized, and the heat that results from exothermic reactions is adequate to smelt the concentrate to produce a liquid matte and molten slag. The liquid matte typically contains 20–50% Ni, 7–25% Cu, 1–40% Fe, and 20–27% S. Furnace matte still contains iron and sulfur that are oxidized in the converting stage. The converter slag from both the nickel and copper converting, which contain approximately 2% Ni, 1.5% Cu, 40% Fe, and 25% SiO_2, are returned to the furnaces to recover the base metal. Oxides form slag that is skimmed off and is processed in an electric furnace prior to discard to recover nickel. The discarded slag typically contains 0.3–0.4% Ni, 0.2% Cu, 39% Fe, and 35% SiO_2 (Ray et al., 2014). In some nickel ore smelting, slag formation is complex because of the presence of MgO in various silicate minerals. The slag is typically iron and silicarich, but with elevated MgO levels. MgO increases the melting point, allowing olivine, $(Mg, Fe)_2SiO_4$, to crystallize out of the melt. This can be countered with silica and lime addition as lime decreases the viscosity of the melt.

For laterite ore processing, a reverberatory, flash, or electric furnace is used to (i) remove free and chemically bound moisture; (ii) reduce the nickel oxide; and (iii) reduce iron content sufficiently to produce ferronickel product. Laterite ores have no significant fuel value and the electric furnace can be used to obtain the high temperatures to accommodate the high magnesia content of the ore. In the matte smelting operation, sulfur may be added to some laterite smelters to produce a matte for processing. This operation produces a matte instead of ferronickel in the electric furnace. The matte is converted to eliminate iron as in the case of sulfide ore processing, which produces converter matte essentially made up of nickel sulfide. This nickel sulfide can be roasted and reduced to produce metallic nickel. To make ferronickel, the concentrate is smelted in an electric furnace at 1550–1650°C (2822–3002°F). During smelting, the reduced nickel and iron melt to form a ferronickel bath with 25–40% Ni. The gangue silicates form a molten slag. The ferronickel is tapped from the furnace and is sent to further refining to oxidize phosphorus and remove sulfur. The slag is discarded. The typical chemical composition of slag is approximately 0.2% Ni, 5.5% Fe, 38% MgO, and 53% SiO_2. The ferronickel is used directly in stainless steel manufacture without any further refining after desulfurizing by the addition of CaC_2 (Ray et al., 2014).

The next step of nickel smelting is to refine the molten matte, which is typically done with one of two processes. With fluid-bed roasting, sulfides are added to the molten matte and the two are roasted together, eventually leaving just the nickel metal. The other process is chloride–hydrogen reduction, in which the molten matte is kept around 950°C until a reaction occurs from the heat and the molten matte turns into just nickel.

Hydrometallurgical processes based on ammonia or sulfuric acid leach are also used to extract nickel. No slag is generated in hydrometallurgical processes.

3.3.2 Basic properties of nickel slag

In terms of chemical compositions, nickel slag is very siliceous that may contain up to 50–55% silica and has high magnesium content. Compared with copper slag, it contains less iron, lime, and alumina. The chemical composition of nickel slag is presented in Table 3.3.

Because nickel slag contains little lime and alumina, its hydration cannot generate the formation of silicate and hydrated lime alumina, which are the main elements responsible for the hydraulic properties of granulated blast furnace slag. Ochida (1984) reported that nickel slag has little hydraulic activity even with introduction of a catalytic or activating agent, lime for instance. Its pseudo-pozzolanic properties are not greatly increased when it is added to mortar and concrete.

In terms of mineralogical properties, nickel slag, essentially made up of a major vitreous phase concentrated in the smallest particles and of a much lesser crystalline phase, is particularly present in the larger particles. This distinction is quite visible to

Table 3.3 Chemical composition of nickel slag (%)

Fe (total)	SiO_2	Al_2O_3	CaO	MgO	MnO	K_2O	Na_2O	S	P_2O_5	Ni
20.7–53.06	29–50.5	<0.10	1.8–3.96	1.56–26.7	0.35–0.36	0.03	0.03	0.36	0.002–0.003	0.16–0.17

Data from Chesner, W. H., Collins, R. J., & MacKay, M. H. (1998). *User guidelines for waste and by-product materials in pavement construction*. FHWA-RD-97-148. Washington, DC: FHWA; Wang, G., Thompson, R., & Wang, Y. (2011). Hot-mix asphalt that contains nickel slag aggregate—Laboratory evaluation of use in highway construction. *Journal of the Transportation Research Board, 2*(2208), 1–8.

the naked eye, and it is possible to see both torn particles that look like broken glass and large, soft, friable particles with honeycomb-like surfaces. There are no free oxides and the reduced crystalline phase is mainly composed of enstatite and forsterite. Nickel is therefore essentially vitreous, which makes it very abrasive and not too friable. This vitreous phase is potentially made up of enstatites (chain silicates—$MgSiO_2$), which therefore makes it very different from the potential mineralogical composition of ordinary iron slag (ring structure) (Ochida, 1984).

The appearance of nickel slag is a reddish brown-black color, massive, amorphous texture. Its unit weight is ~3500 kg/m^3 (~218 lb cf). Air-cooled nickel slag is brownish-black in color. It crushes to angular particles but has a smooth and glassy texture. The specific gravity of air-cooled nickel slag may be as high as 3.5, while the absorption is quite low as 0.37%. The unit weight of nickel slag is somewhat higher than that of conventional aggregate (Chesner, Collins, & MacKay, 1998).

Table 3.4 presents the basic physical and mechanical properties of crushed air-cooled nickel slag.

Table 3.4 **Basic physical and mechanical properties of crushed nickel slag**

Bulk relative density	3.16–3.31
Absorption (%)	0.73–1.25
Unconfined freeze thaw (% loss)	0.2–0.8
Crushed content, one face (%)	100
Micro-Deval abrasion (% loss)	3.7–7.7
Los Angeles abrasion (% loss)	13.3–22
Magnesium sulfate soundness (% loss)	0.5–1.5
Polish stone value	47–56
Aggregate abrasion value	1.8–2.8

Data from Wang, G., Thompson, R., & Wang, Y. (2011). Hot-mix asphalt that contains nickel slag aggregate—Laboratory evaluation of use in highway construction. *Journal of the Transportation Research Board, 2*(2208), 1–8.

Granulated nickel slag is essentially an angular, black, glassy slag "sand" with most particles in the size range of −2 mm (No. 10 sieve) to +0.150 mm (No. 100 sieve). It is more porous, with lower specific gravity and higher absorption, than air-cooled nicked slag. Nickel slag is very abrasive and does not lend itself well to grinding. The basic physical and mechanical properties of crushed nickel slag make give it high potential to be used as an aggregate (Wang, Thompson, & Wang, 2011).

3.4 Lead extraction and lead slag

Lead is a heavy, soft, malleable metal and is used in lead-acid battery production and other applications such as radiation shield, solders, pewters, fusible alloys, weights, bullets, and shot. The lead-acid battery industry accounted for about 90% of the reported US lead consumption during 2013. Lead production has increased more than

90% for the last decade and sevenfold since 1960 (USGS, 2014). The growth is mainly attributed to the demand of the battery market. Lead can be poisonous, if ingested, and can damage the nervous system of humans and cause brain disorders.

Lead is generally produced by roasting sulfide ores to oxide and then reducing the oxide to lead with carbon. Lead and zinc are often related as coproducts in lead and zinc ores and pyrometallurgical processes. The various combinations of slags (ie, lead, lead–zinc, and zinc slags) are similarly produced. In addition to primary mining production, approximately 50% of total lead production worldwide is based on secondary refining of lead, which generates sodium lead slag (Coudurier, Hopkins, & Wilkomirsky, 1985; Hofman, 1918; Štulović et al., 2013).

3.4.1 Lead extraction process and slag formation

Lead exits either in the form of sulfide or oxide. The common minerals in lead ores are galena (PbS, 86.6% Pb, 13.4% S), cerussite ($PbCO_3$, 83.5% PbO, 16.5% CO_2, 77.5% Pb), and anglesite ($PbSO_4$, 73.6% PbO, 26.4% SO_2, 68.3% Pb). Before smelting, the lead sulfide is first separated from the other sulfides and is concentrated. The concentrate may contain 60–80% lead.

The concentrate is roasted to the oxides, which are subsequently reduced by carbon to yield metallic lead. During roasting, the temperature must be carefully controlled because above 800°C (1472°F), PbS tends to fuse (noting that the melting and boiling points of lead are 328°C (622°F) and 1750°C (3182°F), respectively). Roasting is usually done in a Dwight-Lloyd sintering machine. This not only eliminates sulfur content to a large extent but also produces a sinter with required properties, such as strength and porosity, for the subsequent blast furnace operation, during which the sulfur content of the concentrate is reduced from 16–18% to 1–2% (Kokal, 2006).

The blast furnace has traditionally been the most popular furnace for reduction in smelting of lead. Lead can also be processed by electric furnace or imperial smelting process (ISP). Several newer direct and flash smelting methods such as Kivcet, Outokumpu, and Queneau–Schuhmann–Lurgi are also being utilized (Kokal, 2006). Fig. 3.6 presents the major steps of lead extraction.

The lead blast furnace is much smaller than the iron blast furnace. It has a rectangular cross section with the tuyeres located the long sides. A lead blast furnace produces 200–600 tonnes (220–660 tons) of metal per day.

In the blast furnace and ISP processes, lead-sulfide ores are roasted to form lead-oxide sinter, which is charged with limestone and coke to the lead blast furnace or the imperial smelting furnace. In the latter, lead is collected in the furnace bottom where it separates from slag; while zinc vapor exiting the top is condensed (the melting and boiling points of zinc are approximately 420°C and 907°C (788°F and 1665°F), respectively). In the direct and flash processing methods, lead is partially or totally oxidized into the slag, then the slag is treated in an electric furnace with carbon (coal or coke) to reduce oxidized lead into lead bullion (Turkdogan, 1983). Copper is removed from lead by adding sulfur and by several other processes. Further refining is accomplished by oxidizing impurities with air, lead oxide, sodium hydroxide, or sodium-nitrate flux, and by electrorefining (Peacey, 1989).

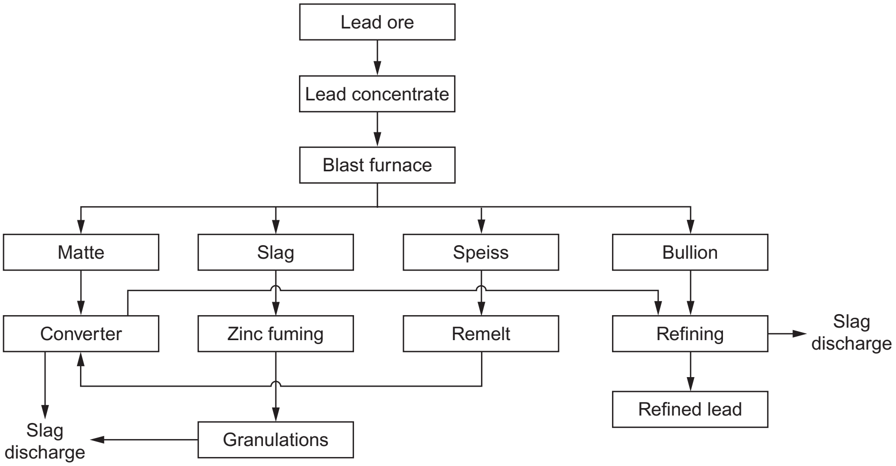

Fig. 3.6 Flow sheet of major steps of lead extraction.

The ISP was developed in England for the simultaneous production of lead and zinc in the blast furnace. While lead is tapped, as is normally done, zinc is recovered by dissolving the outcoming zinc vapors. There should also be a provision for the flow of a stream of molten lead that is continuously recirculated after zinc recovery.

The charge to the lead blast furnace consists of sinter (80–85%), coke (10%), limestone (5–10%), scrap iron (1%), and quartz. Occasionally, limestone is introduced at the sintering stage itself. Limestone and quartz are added to the charge to obtain a slag containing gangue material. The normal composition of the slag is 18–35% SiO_2, 30–38% Fe, 10–20% CaO, and 2–4% Pb. As is evident, a substantial amount of lead goes to the slag (Ray et al., 2014).

The scrap iron in the charge serves a number of useful purposes: (i) it helps in reducing any residual PbS left unroasted in the sintering machines; (ii) it combines with silica present in the charge to form $2FeO{\cdot}SiO_2$, which lowers the melting point of the slag, thus rendering it more fluid at operating temperatures; and (iii) it keeps the lead losses low. For instance, during the initial stages of smelting, lead enters the slag phase as lead silicate, and a major portion of this lead is recovered by adding iron:

$$PbSiO_3 + Fe = FeSiO_3 + Pb$$

and

$$PbO + Fe = FeO + Pb$$

Slag forms during the process with the other three layers of products. The first layer is slag, which has specific gravity of 3.6; the second layer is matte containing copper and other elements with a specific gravity of 5; the third layer is speiss with a specific gravity of 6; and the fourth layer is lead with specific gravity of 11, which is also called *base bullion*. Lead has a rather low melting point, 327°C (621°F). The slag melts at 1200°C (2192°F). The blast furnace product is called *hard lead* because of the hardness imparted by impurities such as copper, antimony, zinc, and silver. After these impurities have been removed, a soft metal with a purity of 99.999% is obtained during subsequent refining (Ray et al., 2014).

The Kivcet flash smelter process is another method to process lead. There are two stages in the Kivcet process. The first one is an oxidation stage in which fine coal and metal sulfides form a hot sulfur dioxide gas and the sulfides of lead and zinc are converted to oxides, and the oxides, silica, and limestone from a semifused slag. In the second stage, the lead and zinc oxides are reduced by a "coke checker," which floats on top of the molten slag. Lead bullion and zinc vapor are produced. Kivcet slag is generated from the Kivcet process (Kokal, 2006).

3.4.2 Basic properties of lead and lead–zinc slag

Lead slag contains trace element contents including Sr, As, Cu, Cl, Sb, Co, Ba, Ni, Zr, Cr, Ce, V, Cd, U, Nd, Mo, Sn, Y, W, Li, Th, Se, In, Rb, Ag, Cs, Bi, Te, and Tl. The contents of these trace elements range from 0.18 to 2470 mg/kg. X-ray diffraction (XRD) patterns indicated that lead slag was mainly composed of kirschsteinite ($CaFe(SiO_4)$), wüstite (FeO), franklinite ($(ZnFeMn)(FeMn)_2O_4$), spinel ($MgAl_2O_4$), and metallic lead (de Andrade Lima & Bernardez, 2011). Secondary lead slag is classified as hazardous waste in the European Waste Catalogue (EWC, 2000). Environmental-related characteristics and utilizations will be further discussed in Chapter 7. Table 3.5 shows the chemical composition of lead slag in a wide range from different sources.

Lead and lead–zinc slags are black to red in color and have glassy, sharp, and angular (cubical) particles. The unit weight of granulated lead and lead–zinc slags can vary from less than 2500 kg/m^3 (156 lb cf) to as high as 3600 kg/m^3 (225lb cf). Granulated lead slag is a black granular material having a high specific gravity of 2.65 to 3.79, due to the high content of iron oxide (Buzatu et al., 2014). Granulated lead and lead–zinc slags tend to be porous, and the absorptions are up to about 5%. Chesner et al. (1998) reported that lead and lead–zinc slags would exhibit adequate and acceptable properties for stability, wear resistance, and friction.

3.5 Zinc extraction and zinc slag

Zinc is extensively used as a protective coating for steel because of its resistance to corrosion by forming an impervious basic zinc carbonate layer. It is also widely used in making alloys such as brasses.

Similar to the other nonferrous metals discussed previously, zinc ores are rarely rich enough to be smelted directly. It is beneficiated. The ore is first crushed and then ground to enable optimal separation from the other minerals. Typically, a zinc concentrate contains some copper, lead, and iron. The concentration is usually conducted at the mine site to keep transport costs to smelters as low as possible (IZA, 2005). Secondary zinc materials, such as recycled zinc oxide, are also processed with zinc sulfide. Over 30% of all zinc produced in the world is from recycled sources. In nonferrous metals, zinc is

Table 3.5 Chemical composition of lead slag (%)

	Fe (total)	SiO_2	Al_2O_3	CaO	MgO	MnO	S	PbO	BaO	ZnO	C	Na_2O	K_2O	TiO_2	CuS
Lead	20–28.7	21.39–35	3.56–10	16–23.11	5.44–10	1.44–5	0.37–2	2–6	–	2–12	2.26	0.27	0.26	0.25	–
Lead–zinc	–	17.6	6.1	19.5	1.3	2–3	2.8	0.8	2	–	–	–	–	–	–
Secondary lead slag	2–20.10	2–12	–	1–9	–	–	3–9.54	5–10		0–0.5	5–10	20–43.2	–	0.60	0.25

Data from Chesner, W. H., Collins, R. J., & MacKay, M. H. (1998). *User guidelines for waste and by-product materials in pavement construction*. FHWA-RD-97-148. Washington, DC: FHWA; de Andrade Lima, L. R. P. & Bernardez, L. A. (2011). Characterization of the lead smelter slag in Santo Amaro, Bahia, Brazil. *Journal of Hazardous Materials, 189*, 692–699; Knežević, M., Korać, M., Kamberović, Ž., & Ristić, M. (2010). *Possibility of secondary lead slag stabilization in concrete with presence of selected additives*. Association of Metallurgical Engineers of Serbia (AMES) Scientific paper, UDC:669.43; Kokal, H. R. (2006). *Fluxes for metallurgy*. Industrial minerals and rocks, commodities, markets, and uses (7th ed.). Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.; Scullion, T., Harris, P., & Rose-Harvey, K. (2010). *Use of copper and lead slag in highway construction: Literature search—Materials use and construction considerations*. FHWA/TX-10/0-6581-TI. Texas Department of Transportation, Austin, TX; Štulović, M., Ivšić-Bajčeta, D., Ristić, M., Kamberović, Ž., Korać, M., & Andić, Z. (2013). Leaching properties of secondary lead slag stabilized/solidified with cement and selected additives. *Environment Protection Engineering, 39*(3), 149–163; Zhang,Y. (2003). *A novel method for metal recovery from zinc and lead slags*. PhD Thesis, University of British Columbia, Vancouver, BC, Canada.

classified as a reactive metal along with aluminum, titanium, magnesium, and uranium. Unlike the nonreactive metals, which can be processed simply in an air atmosphere without any problem of oxidation occurring during reactions when metal oxides are reduced by carbon, the reactive metals frequently require either special equipment or processing to keep them excluded from an air atmosphere with its associated oxidation. Also, because there are complications during oxide reduction with carbon or it is impossible to electrowin from an aqueous solution, they often need sealed furnaces that have a vacuum or inert gas atmosphere (Gill, 1977).

3.5.1 Zinc extraction process and zinc slag formation

The important minerals in zinc ores are sphalerite (ZnS), zincite (ZnO), franklinite [$ZnO(Fe,Mn)_2O_3$], calamine [$Zn_2(OH)_2SiO_3$], and smithstone ($ZnCO_3$). Zinc ores normally contain 5–15% zinc. Approximately 80% of zinc mines are underground mined, 8% are mined from open pits, and the remainder are a combination of both ores (Ray et al., 2014).

Zinc concentrate, which contains approximately 55% zinc, is roasted at a temperature approximately 800°C (1472°F). The methods used to roast the concentrate have an intention to reduce the sulfur content by oxidation to below 1%, so that the zinc oxide product can be reduced by carbon in a retort furnace or blast furnace to zinc metal. The more completely the oxidizing roast is carried out, the better, as any zinc sulfide remaining in the calcines cannot be reduced by carbon during the retort furnace process and will be lost as unreacted in slag and discarded. The methods used for oxidizing roasting of zinc sulfide concentrates are flash roasting, fluid-bed roasting, multiple-heath roasting, and sintering, which can be used singly or in combination. The roasted oxides are agglomerated and then sintered at 1200°C (2192°F) to form lumps for reduction. All are designed to produce material of the physical form and mechanical strength appropriate for the smelting process that follows (Gill, 1977).

The major processes currently used in the world to smelt zinc include the blast furnace process, ISP, electrolytic and electrothermic (St. Joseph Mineral Company), and vertical retort. Horizontal retort is not commonly used anymore (Sinclair, 2005). Fig. 3.7 presents the major steps of the extraction of zinc.

Due to the lower melting and boiling points of zinc at approximately 420°C (788°F) and 907°C (1665°F), respectively, zinc smelting and converting are conducted at lower temperatures than those of copper, noting that the copper has a melting point at 1085°C (1985°F) and copper concentrate does not melt even at a temperature as high as 1500°C (2732°F). In reduction furnaces, retort, for instance, the ZnO is reduced by carbon at about 1200°C (2192°F). The zinc that distills off is collected in condensers.

The horizontal retort process was the dominant one for a very long time. It is now mostly replaced by the vertical continuous retort process (Rosenqvist, 1974). In the horizontal retort process the retorts are first charged with a loose mixture of ZnO and an excess of coke breeze and then heated to a maximum temperature of 1400°C (2552°F) to volatilize zinc, which subsequently condensed.

Vertical retort has a much higher capacity than horizontal retort. The vertical retort developed by the New Jersey Zinc Co. is made of silicon carbide and has

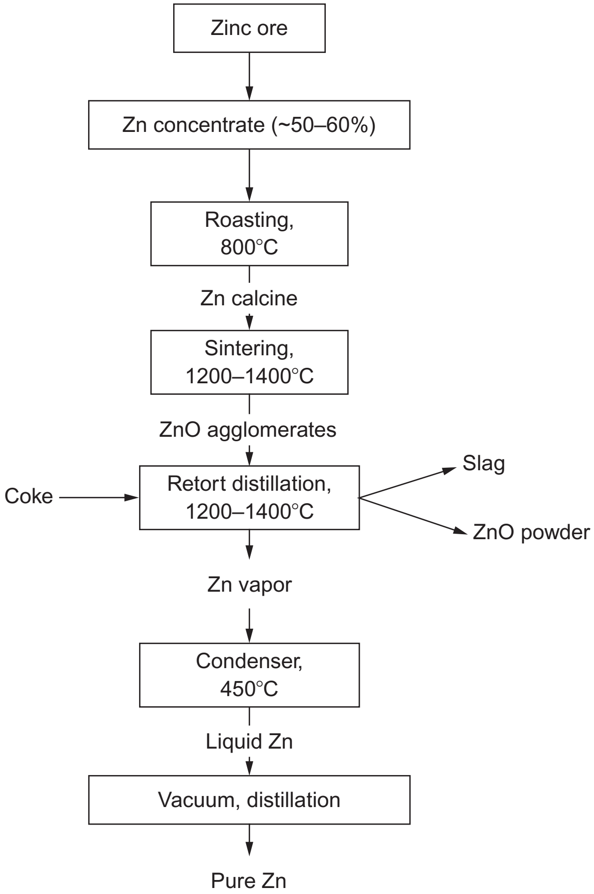

Fig. 3.7 The flow sheet of major steps of zinc extraction.

the shape of a rectangular shaft 10–15 m (33–50 ft) high and 2 m (6.6 ft) long. The retorts are heated from the outside, and a number of retorts are separated by combustion chambers that form a battery, in the same way as in a coking plant (Rosenqvist, 1974). Most vertical retorts are provided with automatic charging and discharging mechanisms that facilitate the handling of raw materials and products. A vertical retort can also be used for electrothermic reduction. It has much higher capacity and can produce 100 tonnes (110 tons) of zinc per day.

The zinc blast furnace process is one of the newest pyrometallurgical processes developed by Imperial Smelting Processing Limited in England. In the ISP, ZnO is reduced by carbon to produce zinc. In the reduction carried out by an ISP blast furnace, the zinc that is evolved in the form of a vapor is condensed by using molten lead. Some of the advantages the ISP include: (i) it is possible to simultaneously smelt low-grade complex mixed charges of zinc–lead ores and concentrates to recover both zinc and lead; (ii) because the overall thermal efficiency is higher, the recovery of zinc becomes less expensive; (iii) a wide variety of furnace sizes are available, the trend being toward units with larger capacities at lower operational cost; (iv) the furnace operation is fully automated; (v) the mechanism is highly robust; that is, it can withstand frequent shutdown and restarts (Sinclair, 2005). Accurate proportioning of the feed (coke, sinter, and burnt lime) is vital to proper furnace operation and each raw material has a weight hopper that enables the precise amount of each component to be weighted out automatically.

The principal reactions in the oxidation of zinc sulfide concentrates are (Sinclair, 2005)

$$\mathrm{ZnS} + 2\mathrm{O}_2 \rightarrow \mathrm{ZnSO}_4$$

$$3\mathrm{ZnS} + 5.5\mathrm{O}_2 \rightarrow \mathrm{ZnO} \cdot 2\mathrm{ZnSO}_4 + \mathrm{SO}_2$$

$$\mathrm{ZnS} + 1.5\mathrm{O}_2 \rightarrow \mathrm{ZnO} + \mathrm{SO}_2$$

$$\mathrm{ZnS} + \mathrm{O}_2 \rightarrow \mathrm{Zn} + \mathrm{SO}_2$$

Besides the reduction of ZnO to Zn, PbO is also reduced to Pb, Fe_2O_3 to Fe, and certain sulfates to sulfides. After the reduction has been completed, the molten slag and lead are taken out of the furnace hearth at a temperature that is approximately equal to the melting point of the slag. The slag runs over the top into a granulation system and is water quenched, granulated, and discarded. Metal values in the slag include approximately 5% zinc and 0.5% lead.

There are limits to the level of zinc in final slag. Generally zinc levels are not reduced much below 6%. The reason is that to reduce more zinc, the oxygen potential is lowered and the tendency to reduce FeO is increased. More metallic iron can cause considerable difficulties in the tapping process, especially at slag temperature of approximately 1350°C (2462°F).

Apart from the zinc content, other slag components are important to control the appropriate melting point and viscosity of the slag, to ensure suitable operation of the hearth, and the ability to tap the furnace and achieve good separation of slag and zinc bullion. Composition adjustment is made by the addition of fluxing components to the sinter feed, but can also dictate the concentrate feed mix and place limits on the intake of particular feed materials. Ratios of major components are targeted in sinter. Additional amounts of some components such as silica will be sourced from the coke and shift these ratios for slag (Sinclair, 2005).

3.5.2 Basic properties of zinc slag

The chemical composition of zinc slag varies depending on the available raw materials to the smelter, but is typically as shown in Table 3.6. Various minerals can be present in zinc slag. In the formation of the minerals in the smelting stage, minor variations of some components can have significant effects. For instance, Al_2O_3 at high levels results in the precipitation of hercynite ($FeO{\cdot}Al_2O_3$), which raises the melting point of the slag but lowers the potential to form metallic iron. Al_2O_3 at low levels has increased potential to form metallic iron. Table 3.6 presents the major chemical composition of zinc slag and Table 3.7 shows the range of component ratios in zinc slag.

Table 3.6 Chemical composition of zinc slag (%)

Fe (total)	SiO_2	Al_2O_3	CaO	MgO	S	PbO	ZnO
25–52	19–40	2–10	15–23	0.5–5	1.1	0–2	0–5

Data from Chesner, W. H., Collins, R. J., & MacKay, M. H. (1998). *User guidelines for waste and by-product materials in pavement construction*. FHWA-RD-97-148. Washington, DC: FHWA; Sinclair, R. J. (2005). *The extractive metallurgy of zinc*. The Australasian Institute of Mining and Metallurgy. Spectrum series, Vol. 13. Carlton, VIC: AUSIMM.

Table 3.7 The range of component ratios in zinc slag

Component ratio	Typical value	Range in value
$CaO:SiO_2$	0.95	0.8–1.4
$FeO:SiO_2$	2.1	1.8–2.9
$FeO:(CaO+SiO_2+Al_2O_3)$	0.9	0.7–1.2

Data from Sinclair, R. J. (2005). *The extractive metallurgy of zinc*. The Australasian Institute of Mining and Metallurgy. Spectrum series, Vol. 13. Carlton, VIC: AUSIMM.

Low-level leaching of metal, in particular lead, typically occurs with prolonged exposure to water (WRAP, 2006).

Granulated zinc slag is glassy material and has the appearance of dark-colored sand and a higher specific gravity than sand due to its metal content. Granulated ISF slag is inherently quite stable, retaining its physical characteristics over time. Granulated zinc slag has physical properties similar to lead and lead–zinc slag. It is black to red in color and has glassy, sharp, angular (cubical) particles. The unit weight of granulated lead, lead–zinc, and zinc slags can vary from less than 2500 kg/m^3 (156 lb cf) to as high as 3600 kg/m^3 (225 lb cf). Granulated zinc slag tends to be porous, with absorptions up to about 5% (Chesner et al., 1998; WRAP, 2006).

3.6 Tin extraction and tin slag

Tin (Sn), having a low melting point at 232°C (450°F), is used in many alloys, most notably in tin–lead solders, which typically contain more than 60% tin. Another large application for tin is corrosion-resistant tin plating of steel. Because of its low toxicity, tin-plated metal is commonly used for food packaging as tin cans, which are made mostly of steel. Tin is extracted from tin ores or from recycled scrap tin. Secondary tin production is increasing. In the United States, only secondary tin is currently produced and no tin ore has been mined or smelted since 1993 (USGS, 2014).

The same as other nonferrous ores, tin ore is beneficiated to obtain concentrate. The concentrate is then reduced in reverberatory, blast, electric, or rotary furnaces. The smelting usually takes two steps. The first step usually involves reduction of the tin concentrate, at a moderate temperature, to produce a tin with low iron content. The second step is to send the molten material (slag), which contains considerable quantities of tin, to the furnace for further reduction to produce tin and slag (Rosenqvist, 1974).

3.6.1 Tin extraction process and tin slag formation

Tin ore is found as cassiterite (SnO_2). Tin also occurs in stannite (Cu_2SnFeS_4), but this is rarely found and is not considered to be a major tin ore. High-grade tin-oxide concentrate is smelted in reverberatory or electric furnaces; and low-grade concentrate is smelted in blast furnaces, kilns, or horizontal furnaces. In the first step of the two-step process, part of the oxides are reduced to metal with the formation of a ferrous–silicate slag containing a small amount of lime and unreduced tin as a tin silicate. The tin slag in the first stage typically contains 30–40% SiO_2, 15–25% FeO, 5–15% CaO, and 5–25% SnO_2. In the second stage, the tin silicate is reduced by iron metal to form iron silicate and an impure tin, which is recycled. Second-stage slag typically contains 24–28% SiO_2, 9–11% Al_2O_3, 20–22% CaO, 12–20% FeO, 2–6% MgO, and impurity metals (Habashi, 1986). Fig. 3.8 presents the flow sheet showing the major steps of tin extraction.

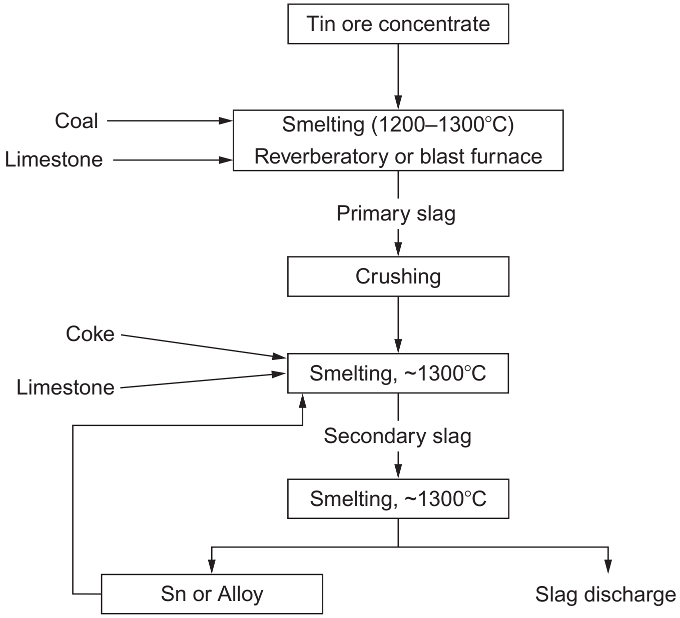

Fig. 3.8 Flow sheet of major steps of tin extraction.

In the conventional reverberatory furnace process, cassiterite (SnO_2) is reduced to tin metal by heating with carbon at 1200–1300°C (2192–2372°F). Tin concentrate is smelted to resmelted slag for additional tin recovery. The furnace charge consists of tin ore (cassiterite), a carbon reducing agent (coke), and limestone and silica fluxes. The quantity of coke and flux is carefully adjusted so as to produce an almost neutral slag (ie, acid-to-base ratio is 1). The smelting takes 10–12 h. In the second stage, additional flux, limestone, coal, and iron scrap that facilitates the reduction of the tin oxide present in the slag are used. The second slag, which contains a much lower amount of tin, is also smelted to recover its tin content. Finally, the molten slag is tapped into a settler from which the slag overflows. After tapping from the furnace the molten slag is quenched, granulated in water, and solidifies into glass-like material. Tin is then refined by pyrometallurgical refining or electrolytic refining and tin slag is discarded (Ray et al., 2014). Tin slag contains lime, iron, silica, and a small amount of heavy metals. The slag also contains naturally occurring radioactive materials such as uranium and thorium and their decay products. The normal composition of the molten slag is 35% SiO_2, 30% CaO, 15% FeO, and 20% SnO_2 (Yusof, 2005). The tin in this stage is subsequently recovered from the slag.

3.6.2 Basic properties of tin slag

The wide range of chemical composition of tin slag from different sources is presented in Table 3.8. Tin slag contains mainly SiO_2, CaO, and FeO in relatively wide ranges. Tin slag may also contain a very small amount of SnO, ZnO, and a trace amount of cadmium (Cd).

Tin slag is a fused glassy-like material containing lime, iron, and silica and small amounts of heavy metals.

The study on granulated slag by Yusof (2005) indicated that the granulated tin slag has a maximum particle size of 16 mm (0.6 in.). Only 2–3.4% of the tin slag particles had a size between 10 and 16 mm (0.4 and 0.6 in.). Most of the tin slag was retained on 0.6 mm (No. 30 sieve) sieve and passing 3.35 mm (No. 6 sieve). The tin slag had a very small amount of filler; that is, only 0.5% of the particles were less than 0.075 mm (No. 200 sieve). The particle size distribution indicates a nearly vertical curve in the mid-size range and flat and near zero in the small-size range of tin slag.

The granulated tin slag is glassy and black in color. Most of the tin slags with particle size greater than 10 mm (3/8 in.) have a rounded shape. However, overall angular shapes are more dominant for tin slag. The proportion of elongated and flaky particles in any tin slag sample was insignificant. The apparent particle density is 3590 kg/m^3 (224 lb cf), and particle density on an oven-dried basis is 3350 kg/m^3 (209 lb cf). When a comparison is made between tin slag, other slags, and natural aggregates, the density value of tin slag seems to be relatively similar to that of steel slag and copper slag. The water absorption of tin slag was measured at 1.97%. The value is moderate when compared with other slags.

In general, tin slag showed satisfactory performance in terms of toughness tests. Ten percent fines value (TFV) was conducted by Yusof (2005) to check the crushing

Table 3.8 Chemical composition of tin slag (%)

	SnO	ZnO	Fe (total)	SiO_2	Al_2O_3	CaO	MgO	MnO	Pb	TiO_2	WO	Cd
Content (%)	0.1–2.8	<0.3	0.9–27.7	12–41	4.7–13	11–29	2–16	0.4–3.7	<0.01	4–5	2	<0.0001

Data from Gaballah, E. A., Meyer-Joly, M.-CH., & Malau, K. (1992). A possible method for the characterization of amorphous slags: Recovery of refractory metal oxides from tin slags. *Metallurgical Transactions B, 23*(3), 249–259; Tylecote, R. F. & Earl, B. (2010). The composition of tin slags from south-west of England. *World Archaeology*, *20*(3), 434–445; Yusof, M. A. W. (2005). *Investigating the potential for incorporating tin slag in road pavements*. PhD Thesis, University of Nottingham, Nottingham, UK.

resistance of granulated tin slag aggregate subjected to loading. In this test, fine aggregates are defined as those passing a 2.36 mm (No. 8) sieve. The results indicated that the TFV was unduly low. This might be caused by the samples with finer particles than the standard sizes required and the needle-shaped particles that would have an affect on the TFV values.

3.7 Summary

In contrast to iron ores that can be smelted directly in iron blast furnace, most nonferrous metal ores require some treatment prior to smelting to increase their chemical purity or to better utilize their physical properties to facilitate the extraction of the metal. Compared with iron- and steelmaking, nonferrous metal production has varied and different extraction techniques. The selection of the extraction methods depends on (i) the particular raw material or the particular combination of raw materials used; (ii) the physical nature of the ore; and (iii) its chemical composition. Although hydrometallurgy and electrometallurgy have been developed over the last hundred years, pyrometallurgy still remains the principal means of nonferrous metal extraction, both in the number of applications and in the tonage of metal produced.

Similar to iron and steel slags, nonferrous slags are basically nonmetallic byproducts from nonferrous metal extraction. Nonferrous slags contain various oxides existing in the form of solid solution. Nonferrous slag may contain trace amounts of oxides of heavy metals that iron blast furnace and steel slags do not have. It is noted that some nonferrous slags are classified as hazardous waste; lead and zinc slag, for example. This means the costs of disposal of these slags to hazardous landfill are significantly higher. All these factors bring the challenges and imperativeness to researchers in exploring the right usages and classifications for nonferrous slag.

Questions

3.1 What are the major steps to extract nonferrous metal?
3.2 What is reduction smelting?
3.3 What is matte smelting?
3.4 What is converting?
3.5 Why are nonferrous ores concentrated prior to smelting?
3.6 What are the products from matte smelting in copper production?
3.7 Why does granulated copper slag have hydraulic reactivity?
3.8 What are the products from converting in copper production?
3.9 Why does nickel slag have little hydraulic reactivity?
3.10 Why are lead, lead–zinc, and zinc slag sometimes produced simultaneously?
3.11 Describe the physical properties of copper and nickel slag.

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Nonmetallurgical slags

4

4.1 Introduction

In a broad sense, the definition of slag can be extended to the fused agglomerated materials that are generated during the production of a base element to separate it from the impurities in the raw materials, for example, element phosphorus and phosphorus slag; or from coal combustion and incinerating process, for example, boiler slag from power generation and incinerator slag from incinerating municipal solid waste (MSW). These by-products or residues undergo high-temperature processes in a molten condition and subsequently are cooled under ambient air conditions or by water quenching, becoming solid and hard materials. In this broad sense, slag has been extended to the agglomerated materials from nonmetallurgical processes. In this chapter the focus is placed on the formation of phosphorus slag, boiler slag, and municipal solid waste incinerator (MSWI) slag, and their basic properties.

Phosphorus slag is formed during the elemental phosphorus production process. When phosphate rock, phosphorus concentrate, and fluxes are smelted in an electric arc furnace under temperatures of 1400–1500 °C (2552–2732 °F), molten slag is formed and tapped out from the furnace and goes through an air-cooling or water quenching process. The elemental phosphorus is separated from the impurities during the slagging process.

Similar to nonferrous metals production, the ore (ie, phosphate rock) is normally beneficiated before the smelting because the ores normally contain low phosphorus content. For example, for the phosphate rock produced in Florida, the content of P_2O_5 ranges approximately from 28% to 30% (Zhang, 2015).

In phosphorus production, large quantities of raw materials have to be handled and processed. To produce one tonne of elemental phosphorus, approximately 12.7 tonnes of solid materials are required. This typically includes 9.5 tonnes of phosphate rock, 1.5 tonnes of coke, and 1.7 tonnes of silica rock. To produce 1 tonne of elemental phosphorus, approximately 8–10 tonnes of phosphorus slag is produced (Barber, 1975; Corbridge, 1995; Zhou, Shu, Hu, & Wang, 2010).

Worldwide phosphate rock mine production in 2013 was 224 million tonnes (246 million tons) increased by 3.2% from 217 million tonnes (239 million tons) in 2012 (USGS, 2014). In the United States, phosphate rock mining is the fifth largest mining industry in terms of quantity of material mined. In 2013 the total production of phosphate rock in the US was estimated at 32 million tonnes (35 million tons). Most of the phosphate production goes to the making of fertilizers (USGS, 2014). In 2013, China was the largest producer of sedimentary phosphorite, which accounted for approximately 43% of the worldwide output of phosphate rock mining, and the United States came in second at 15% of the worldwide production (USGS, 2014).

In the phosphate industry, approximately 5% of the phosphate rock is processed via the electric arc furnace process to make elemental phosphorus (Corbridge, 1995; Goldwhite, 1981; Zhang, 2015). The remainder is processed using the "wet method"

The Utilization of Slag in Civil Infrastructure Construction. http://dx.doi.org/10.1016/B978-0-08-100381-7.00004-5

to produce phosphoric acid and other phosphorus compounds. During the wet process, phosphogypsum, a by-product of this process, is produced. In 2013, approximately 1.5 million tonnes of element phosphorus is produced worldwide. The total annual phosphorus slag generated from the elemental phosphorus production therefore can be estimated as approximately 12–15 million tonnes (13.2–16.5 million tons).

Boiler slag is the agglomerated residues formed in coal-burning facilities; coal combustion furnaces in thermal power stations, for instance.

Boiler slag is formed at the base of the furnaces, mainly slag-tap and cyclone types, at temperatures of 1500–1700 °C (2732–3092 °F). The molten slag is collected and quenched with water-forming boiler slag. When the molten slag comes in contact with the quenching water, it fractures, crystallizes, and forms pellet-shaped particles. Boiler slag is a vitreous, grained material made up of hard, black, and angular particles with a smooth and glassy appearance (ECOBA, 2015).

Boiler slag is one of the coal combustion products (CCPs), along with fly ash, bottom ash, and flue gas desulfurization (FGD) gypsum. Coal, as a source of energy, has played a very significant role in generating electricity in (approximately) the past 150 years. In 2013, approximately 67% of the electricity generated in the United States was from fossil fuel (ie, coal, natural gas, and petroleum) with 39% attributed from coal. Worldwide, electricity generated by burning coal is approximately 41%. In some countries this number is higher. For example, in South Africa, it is 93%, Poland 87%, China 79%, Australia 78%, Kazakhstan 75%, India 68%, Israel 58%, and Czech Republic 51%. According to the International Energy Agency (IEA, 2015), in 2010, 7200 million tonnes (7920 million tons) of coal was consumed in the world, which increased 60% in 10 years from 2000.

Huge amounts of CCPs are produced each year. According to the American Coal Ash Association (ACAA), combustion of coal in the United States alone generated approximately 120 million tonnes (132 million tons) of CCPs in 2010, which included approximately 62 million tonnes (68.2 million tons) of fly ash, 17 million tonnes (18.7 million tons) of bottom ash, 30 million tonnes (33 million tons) of FGD materials, and 2 million tonnes (2.2 million tons) of boiler slag. Although boiler slag accounted for approximately 15% of the total CCPs generated, the utilization rate of boiler slag is higher than other CCPs; that is, fly ash, bottom ash, and FGD gypsum. In the United States, the utilization rate of boiler slag was 66.16% in 2013, while the utilization rates for fly ash, bottom ash, and FGD gypsum were 43.67%, 39.02%, and 48.85%, respectively. In Europe, the utilization rates of CCPs are generally higher than those of the United States. The utilization rate in Europe for boiler slag was 100% in 2007. For fly ash and bottom ash, the utilization rates were 49% and 51%, respectively (ACAA, 2015). Although the total production of boiler slag accounts for a relatively small portion of the total CCPs, the successful applications of boiler slag can be a reference to the utilization of other CCPs, especially fly ash and bottom ash, as the chemical and mineral composition of boiler slag, bottom ash, and fly ash are typically very similar, consistent, and uniform, if the coal used is from the same source, and they all are defined as nonhazardous materials.

Incinerator slag, most often is generated from the process of incinerating MSW. Incinerating is one of the three most frequently selected methods for MSW treatment along with landfilling and composing. Incineration is the combustion of MSW in a controlled manner to destroy it or transform it into less hazardous, less bulky, or more controllable constituents. Incineration may also be used to treat a wider range of waste streams, including commercial, clinical, and certain types of industrial waste (Cheremisinoff, 2003).

Solid waste management practices still differ widely throughout the world. MSW incineration is becoming increasingly important for waste management. In some countries, for example, countries in Europe, the European regulations prohibit storing of untreated waste in landfills (Müller & Rübner, 2006). In the United States and some other industrialized countries, the disposal of MSW is one of the more serious and controversial urban issues facing local governments. In the United States, approximately 84% of the MSW goes to landfills, while in Japan and most European countries over 70% of their MSWs are incinerated (Cheremisinoff, 2003).

It should be noted that boiler slag and MSWI slag are two different materials. Boiler slag, like other CCPs, results from burning coal under controlled conditions. The US Environmental Protection Agency (EPA) has determined that CCPs are nonhazardous and have excluded CCPs from their list of hazardous wastes. Incinerator slag is obtained as a result of burning MSW or combinations of MSW and other wastes. The chemical and mineral composition of incinerator slag vary because of the wide variety of MSW materials burned (Ramme & Tharaniyil, 2013).

4.2 Phosphorus slag

Phosphorus element (P_4) is one of the 20 most abundant elements on Earth. Phosphorus is not found free in nature and almost always occurs in the fully oxidized state as phosphate. While fluoroapatite, $Ca_5(PO_4)_3$, is the ideal single mineral containing phosphorus, the most common phosphorus minerals are apatites, which contain the composition of $Ca_5(PO_4,CO_3)_3$ (F,Cl,OH) (Goldwhite, 1981). The mineral apatite is the most abundant and widespread phosphorus compound and is commonly used as raw material for making phosphorus products.

Mineral phosphates have been processed and used as fertilizers since the 1840s (Goldwhite, 1981). Phosphorus is one of the three major essential plant nutrients, along with nitrogen and potassium, and essential to every living cell. The organic phosphatic compound deoxyribonucleic acid provides the genetic code for life, and adenosine triphosphate (ATP) is essential for cellular energy conversion. Phosphoric acid is the most important industrial commodity based on phosphorus. Phosphorus is also extensively used in other applications; for example, in the production of synthetic detergents, animal foodstuffs, dental materials, toothpaste, building materials, and for water treatment and metal treatment (Corbridge, 1995).

Most phosphorus consumed worldwide is in the form of phosphates. Element phosphorus is only required for a limited production. About 5% of the phosphate rock product is processed to produce element phosphorus. The remainder is to make phosphoric acid. There are various allotropic forms of phosphorus but only two forms have commercial significance: white, sometimes called yellow, and red phosphorus. White phosphorus, which is the most commercially important, accounts for 99% of element phosphorus production worldwide; the remaining 1% is mainly red phosphorus. Most phosphorus is used to make phosphoric acid of high purity for some food processing and for etching semiconductors. Red phosphorus is mainly used in pyrotechnics and matches.

The major mineral phosphate, apatite, occurs mostly as a sedimentary deposit that is named phosphorite, or "phosphate rock." Most phosphorite is believed to be of marine origin. It is amorphous and associated with calcium carbonate. Other common impurities in phosphorites are iron (III) oxide, alumina oxide, and silica, but a variety of other metals, including uranium, are found in trace amounts (Corbridge, 1995). It occurs widely, but important sources are in the United States (Florida, North Carolina), Morocco, Tunisia, Jordan, Saudi Arabia, Russia, and China. Table 4.1 presents the chemical composition of phosphorus ores from Florida and Khouribga.

Table 4.1 **Chemical compositions of major phosphorus ores (%)**

	P_2O_5	CaO	Fe_2O_3	Al_2O_3	SiO_2	CO_2	F
Florida, USA	34.4	49.3	1.2	0.95	4.21	3.12	3.8
Khouribga Morocco	37.2	54.2	0.1	0.39	0.97	2.64	4.2

Data from Corbridge, D.E.C. (1995). *Phosphorus: An outline of its chemistry, biochemistry and uses*, 5th ed. Amsterdam, The Netherlands: Elsevier.

4.2.1 Phosphorus production and phosphorus slag formation

As most phosphoric acid for fertilizer production does not need to be very pure and can be made more economically directly from phosphate rock and not from the element phosphorus, two processing routes were developed.

The two major methods to process phosphate rock are the wet method and the thermal method, each of which produces different products. Fig. 4.1 presents the two major processing methods for phosphate rock, their products, by-products, and typical end uses of the products (Corbridge, 1995; Goldwhite, 1981; Yapijakis & Wang, 2004).

It should be noted that phosphorus slag is generated in the thermal processing of phosphate rock during the production of element phosphorus. In the wet process, the by-product generated is regarded as "phosphogypsum," which does not undergo high-temperature smelting and is different mineralogically and physically from phosphorus slag.

The commercial wet process for phosphorus acid production consists essentially of grinding the apatite phosphate rock, reacting it with acid, and then separating the insoluble calcium sulfate (phosphogypsum) by filtration. In practice the calcium sulfate tends to form an insoluble layer on the phosphate rock, which slows down further reaction. To minimize this effect, the rock is initially treated with recirculated phosphoric acid to produce soluble monocalcium phosphate (Corbridge, 1995):

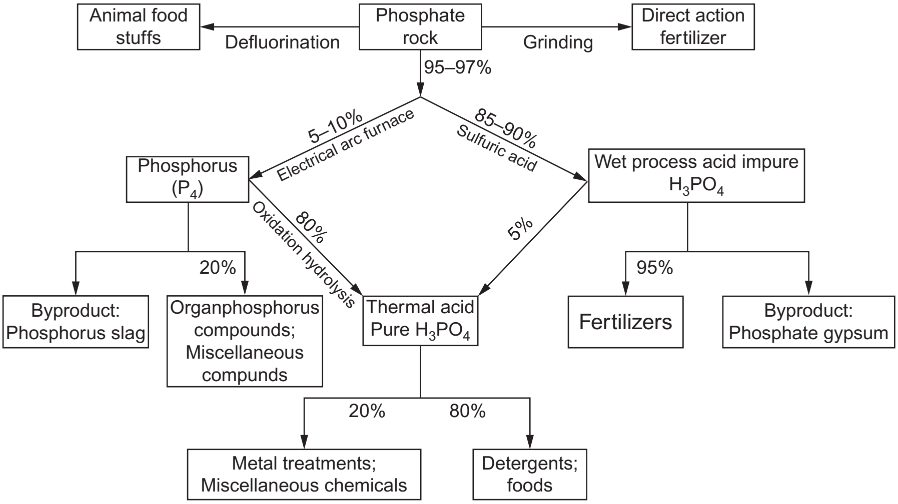

Fig. 4.1 Processing of phosphate rock and commercial utilization of the phosphate rock and by-product generation.

$$3Ca_3(PO_4)2CaF_2 + 14H_3PO_4 \rightarrow 10Ca(H_2PO_4)_2 + 2HF$$

which can then react with sulfuric acid:

$$10Ca(H_2PO_4)_2 + 10H_2SO_4 + 10 \times H_2O \rightarrow 20H_3PO_4 + 10CaSO_4 \times H_2O$$

The precipitated calcium sulfate can contain phosphoric acid, up to 3% lost during the process. The wet process consumes much less power compared with the thermal process. However, viscosity and filtration problems may arise in the wet process, when a high level of impurities are present in the ores. The thermal process can better cope with lower-grade ores. The main producers of element phosphorus globally are in Kazakhstan, China, and the United States. By using the thermal electrothermal method to produce each tonne of phosphorus, approximately 14,000 kW electricity is required. Because the energy demand of elemental phosphorus production by an electrothermal process is very high, its manufacture is normally carried out where comparatively cheap energy is available.

Using the thermal method to commercially produce element phosphorus started in the 1890s when white phosphorus was obtained commercially, in approximately 90% yield, by heating a mixture of phosphate rock (apatite), sand (silica), and coke in an electric furnace to a temperature of approximately 1450 °C (2642 °F). Up to the present, the electric arc furnace is still the major facility used to produce phosphorus from its ore. Fig. 4.2 presents a simplified, schematized phosphorus electric arc furnace. A typical furnace has a diameter of approximately 12 m (39.4 ft), height of 8 m (26.2 ft), and a capacity to produce 30,000 tonnes (33,000 tons) of phosphorus a year.

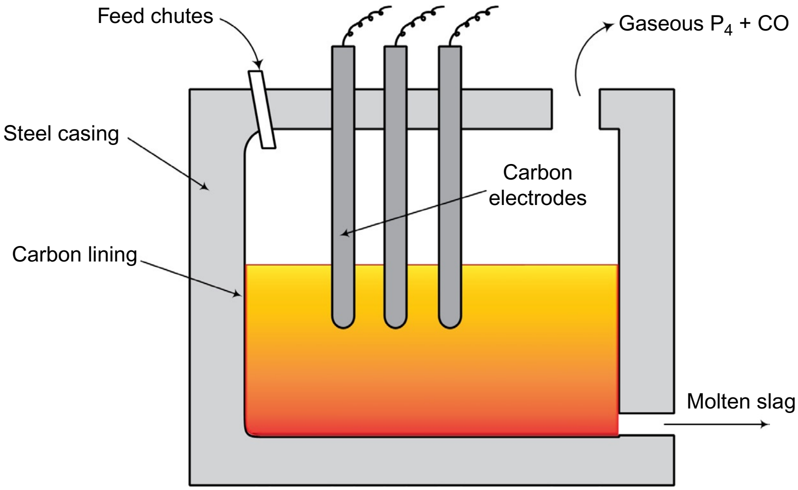

Fig. 4.2 Simplified schematized phosphorus electric arc furnace.

To increase the thermal production efficiency, the raw materials are processed as uniformly as possible. The phosphate rock is heated in a rotating calciner, which results in the fusion of small particles to form the hard nodules required for satisfactory furnace operation. The furnace, containing three vertical carbon electrodes, is fed with a mixture of coke, sand, and phosphate rock in a ratio of, typically, 16:30:100.

In spite of the heat of the combustion of the coke, the reaction is strongly endothermic and, as indicated, requires an electrical input of approximately 14,000 kWh per tonne of phosphorus produced. An "acid displacement" mechanism is considered the most likely course of reaction in thermal reaction:

$$2Ca_3(PO_4)_2 + 6SiO_2 \rightarrow 6CaSiO_3 + P_4O_{10} \text{ and } P_4O_{10} + 10C \rightarrow P_4 + 10CO$$

Gaseous phosphorus and carbon monoxide, from the top of the furnace, are passed into a spray of water at 70 °C (158 °F). Most of the phosphorus condenses with melting point at 44 °C (111 °F). Condensation is completed using cold water. The carbon monoxide is either burnt off or recycled as a source of fuel. The phosphorus vapor is taken from the top of the furnace, condensed, and collected underwater. The yellow liquid product is liable to contain As and Sb in quantities up to approximately 100 ppm, as well as some Si, C, Fe, and F. Decolorization and partial purification can be effected by filtering the liquid element through active carbon, while repeated washing will reduce the Si content. Steam distillation will reduce the As and Sb content to ~2 ppm (Corbridge, 1995).

In the electric furnace the fluorine from the fluorapatite is evolved mainly as gaseous silicon tetrafluoride, which is removed by scrubbers according to the equation, but some remains in the calcium sulfate and the acid product:

$$3SiF_4 + 2H_2O \rightarrow 2H_2SiF_6 + SiO_2$$

Molten calcium silicate slag produced in this step is tapped off from time to time from the base of the furnace during continuous furnace operation. Some phosphorus combines with iron impurities to form an alloy of iron and phosphorus known as "ferrophosphorus," a high-density product that can also be tapped off. For every tonne of phosphorus extracted, approximately 0.3 tonnes (0.33 tons) of ferrophosphorus are obtained. The ferrophosphorus can be added to sheet steel to prevent sticking of sheets or added to iron to improve stiffening. It can also be used as an additive for anticorrosive paints, as a source of phosphorus in metallurgy, or as a filler in radiation proof concrete.

4.2.2 Basic properties of phosphorus slag

The chemical composition of phosphorus slag is relatively consistent and falls in relatively narrow ranges. Table 4.2 presents the typical chemical composition of phosphorus slag. The remaining composition contains metals, including varied quantities of rare earth elements. Some phosphorus slag may have a small degree of natural radioactivity.

Table 4.2 **Chemical composition of typical phosphorus slag (%)**

CaO	SiO_2	Al_2O_3	K_2O	SO_3	MgO	F	P_2O_5	Na_2O	Fe_2O_3	MnO
44.1–48.5	40.3–41.3	4.9–8.8	0.7–1.2	0.6	0.5–1.75	2.8	0.5–2.9	0.3–0.4	0.17–0.2	0.2

Data from Chesner, W.H., Collins, R. J., & MacKay, M.H. (1998). *User guidelines for waste and byproduct materials in pavement construction*. FHWA-RD-97-148. Washington, DC: FHWA; Corbridge, D.E.C. (1995). *Phosphorus: An outline of its chemistry, biochemistry and uses*, 5th ed. Amsterdam, The Netherlands: Elsevier; Zhou, J., Shu, Z., Hu, X., & Wang, Y. (2010). Direct utilization of liquid slag from phosphorus-smelting furnace to prepare cast stone as decorative building material. *Construction and Building Materials, 24* (2010), 811–817.

Similar to iron blast furnace slag, molten phosphorus slag can be air-cooled or granulated. Air-cooled phosphorus slag has black to dark gray, vitreous (glassy) appearance, and irregular shape. Individual particles are generally flat and elongated, with sharp fracture faces similar to broken glass. The crushed material has a unit weight of 1360–1440 kg/m^3 (85–90 lb cf), which is less than that of conventional aggregate, with absorption values of about 1.0–1.5%.

Air-cooled phosphorus slag has high abrasion resistance and favorable frictional resistance properties. Air-cooled phosphorus slag aggregates also exhibit very good soundness (high resistance to freeze–thaw deterioration) and good resistance to mechanical degradation.

Granulated phosphorus slag is made up of regularly shaped and angular particles, mostly between 4.75 mm (No. 4 sieve) and 0.075 mm (No. 200 sieve) in size. It is more porous than air-cooled slag and consequently has lower specific gravity. Granulated phosphorus slag is more vesicular than air-cooled slag and consequently has lower unit weight. Granulated phosphorus slag has a unit weight of 880–1000 kg/m^3 (55–62 lb cf) and has a higher absorption than air-cooled slag due to its more vesicular nature (Chesner, Collins, & MacKay, 1998).

4.3 Boiler slag

Boiler slag is defined as solid, black, angular particles that is resulted from molten coal ash collected at the base of the coal-burning slag-tap or cyclone boiler, quenched with water and shattered into the particles with a smooth, glassy appearance (Kalyoncu, 2001).

The "raw material" from which the boiler slag is produced is coal. At the present time, most of the mined coal in the world is used for electricity production. This operation mainly involves the combustion of pulverized coal. Based on its reserves, coal may be classified into four types that can be used in coal-fired power stations: anthracite, bituminous, subbituminous, and lignite. Anthracite coal has the highest carbon content and the lowest moisture and ash content. Anthracites are now very much less widely distributed in the world than are bituminous coals. Anthracite burns slowly and makes a good heating fuel for homes. The United States has approximately 6.6 billion tonnes (7.26 billion tons) of anthracite, most of which can be found in Pennsylvania (CAER, 2015; Kalyoncu, 2001).

Bituminous coal is the most common type of coal that constitutes the bulk of the so-called hard coals. "Bituminous" is used to classify coal based on its content of fixed carbon, volatile matter, and heating value. Bituminous, which contains 78–90% carbon content, generally has a high heating value and low moisture content in the range of 1–13%. It is mainly used to generate electricity and coke for the metallurgy industry.

Subbituminous coal is between bituminous coal and lignite in rank, which has 78–79% carbon, an intermediate heating value, volatile matter content, and moisture content in the range of 10–20% (CAER, 2015; Kalyoncu, 2001).

Lignite is the lowest-rank coal that has a low heating value with 65–73% carbon and a high moisture content in the range of 20–40%. Lignite is fairly soft and can be brown or black in color. It is burned to generate electricity (CAER, 2015; Williams, Pourkashanian, Jones, & Skorupska, 2000). Prior to use, coal is usually sized, cleaned, pulverized or crushed, and blended to meet commercial specifications that involve criteria of sulfur content, ash, volatiles, and calorific value.

4.3.1 Coal combustion and boiler slag formation

In general, coal contains complex minerals that cause the coal ash to melt over a temperature range rather than at a fixed temperature. The range of the temperatures is specified in ASTM D1857 (ASTM, 2010): Standard Test Method for Fusibility of Coal and Coke Ash. A coal ash cone, 19 mm (3/4 in.) high and with an equilateral triangle base 6.4 mm (1/4 in.) on each side, is placed in an oven. Temperatures are reported for a reducing or oxidizing gas environment. The initial deformation temperature (IDT) occurs when rounding of the cone tip first occurs. The softening temperature (ST) occurs when the cone has fused to produce a lump, which has a height equal to its base. The hemispherical temperature (HT) occurs when the lump height is half the length of its base. The fluid temperature (FT) occurs when the fused mass has spread out in a nearly flat layer with a maximum height of 1.6 mm (No. 12). Quantitative equations for IDT, ST, HT, and FT temperatures were developed by Seggiani and Pannocchia (2003). In the equations, the temperatures are functions of the content of nine oxides in coal ash. The FTs of coal ash range from approximately 1200 °C (2192 °F) for lignite to 1460 °C (2660 °F) for bituminous.

Pulverized coal-fired boilers have been developed and used since the 1900s and are currently the most widely accepted technology for large-scale coal-fired heat and electricity generation. They are termed *coal-fired boilers*. The boiler systems normally use subcritical pressure (<221.2 bars) steam cycles with superheated and single reheated steam, which can increase thermal efficiencies in the range of 35–38%, depending on feedstock, steam conditions, condensing pressure, and plant size (Williams et al., 2000).

As indicated, coal ash resulting from different coals can be a complex and variable mixture of minerals that melt over a range of temperatures. Some furnaces operate near 1000 °C, which is under the melting point of ash. This maximizes feed conversion while avoiding temperatures that would make the ash sticky. Some furnaces, moving bed furnace, for instance, are designed for operation at higher temperatures up to 1400–1600 °C (2552–2912 °F) so that the ash is allowed to melt and flows out as slag. Melting the ash to form a slag involves an endothermic heat of melting (Bell, Towler, & Fan, 2011):

$$\text{Ash}(\text{s}) \rightarrow \text{Slag}(\text{l})\,\Delta H^{\circ}_{\text{melt}} = \text{positive, variable}$$

A flow diagram depicting the coal combustion and generation of CCPs is presented in Fig. 4.3.

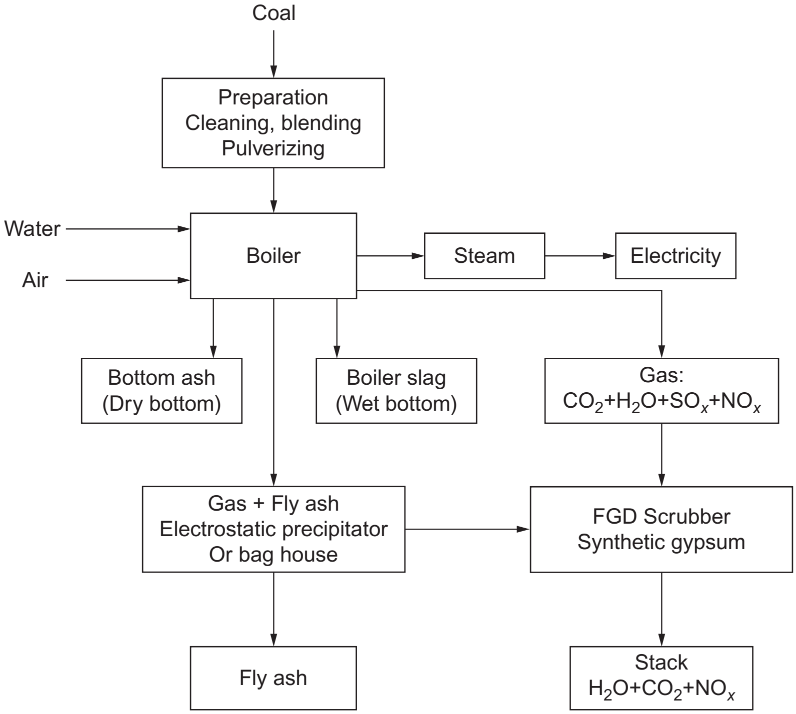

Fig. 4.3 Coal combustion and coal combustion products generation.

From the state of coal ash, coal-firing boilers are referred as *wet-bottom* and *dry-bottom boilers*. Most of the coal-fired boilers are dry-bottom boilers, which means they are operated under conditions where the ash is removed as a dry particulate solid (ie, bottom ash), which forms by chemicophysical reactions. If a furnace temperature is higher than the ash fusion temperature, the furnace is called a wet-bottom furnace, which indicates the ash is in a liquid state. A wet-bottom boiler is a boiler that contains a wet bottom. It is a type of boiler used for pulverized fuel firing. In a wet-bottom boiler the bottom ash is kept in a molten state and tapped off as a liquid. Wet-bottom boiler slag (WBBS) is a term used to describe the molten condition of the ash as it is drawn from the bottom of the boilers. An advantage is that the end product in this process has a higher value compared to that of a dry-bottom boiler. A wet-bottom boiler is preferred for low-volatile coals that produce a lot of ash. Because the investment and maintenance costs are higher, a wet-bottom boiler is built less often.

There are two types of wet-bottom boilers: the slag-tap boiler and the cyclone boiler. The slag-tap boiler burns pulverized coal and the cyclone boiler burns crushed coal. In each type, the bottom ash is kept in a molten state and tapped off as a liquid. Both boiler types have a solid base with an orifice that can be opened to permit the molten ash slag that has collected at the base to flow into the ash hopper below. The ash hopper in wet-bottom furnaces contains quenching water. When the molten slag comes in contact with the quenching water, it fractures instantly, crystallizes, and forms glassy particles. The resulting boiler slag is a coarse, hard, black, angular, glassy material. At intervals, high-pressure water jets wash the boiler slag from the hopper pit into a sluiceway that then conveys it to a collection basin for dewatering, possible crushing or screening, and either disposal or reuse. When pulverized coal is burned in a slag-tap furnace, as much as 50% of the ash is retained in the furnace as boiler slag. In a cyclone furnace, which burns crushed coal, some 70–80% of the ash is retained as boiler slag; the rest, approximately 20–30%, leaves the furnace in the form of fly ash (Chesner et al., 1998; Ramme & Tharaniyil, 2013).

WBBS is a porous, glassy, granular particle that is primarily regarded as a single-sized coarse to medium sand. This material is essentially composed of silica, alumina, and iron with small amounts of calcium, magnesium, and sulfates. As long as it is collected from wet-bottom boilers (otherwise it would be considered bottom ash), the composition of the material is governed by the coal source not by the type of furnace (Griffiths & Krstulovich, 2002).

4.3.2 Basic properties of boiler slag

It is difficult to predict the properties of coal ash produced and the tendency to form slags. This is because of the variation of the composition of the main inorganic constituents in the coal, and the difficulty of relating the composition to actual performance in practice (Williams et al., 2000).

Boiler slag is composed principally of silica, alumina, and iron, with smaller amounts of calcium, magnesium, sulfate, and other compounds. Table 4.3 presents a chemical analysis of selected samples of boiler slag from bituminous and lignite coals. Normally, the chemical composition of boiler slag samples is generally similar to that of bottom ash, if the same coal is used, even though the production process of boiler slag and bottom ash is relatively different.

Table 4.3 Chemical composition of boiler slag

	Al_2O_3	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Boiler slag from bituminous coal	48.9–53.6	21.9–22.7	10.3–14.3	1.4	5.2	0.7	0.1
Boiler slag from lignite coal	40.5	13.8	14.2	22.4	5.6	1.7	1.1

Data from Chesner, W.H., Collins, R. J., & MacKay, M.H. (1998). *User guidelines for waste and byproduct materials in pavement construction*. FHWA-RD-97-148. Washington, DC: FHWA; Ramme, B.W., & Tharaniyil, M.P. (2013). *Coal combustion products utilization handbook*, 3rd ed. Milwaukee, WI: We Energies.

From Table 4.3, it can be seen that boiler slag derived from lignite or subbituminous coals has a higher percentage of calcium than the boiler slag from anthracite or bituminous coals. Deleterious materials, such as soluble sulfates or coal pyrites, may exist in boiler slag, which can be removed before use. Pyrites can be removed from the coal before it is burned using sink-float techniques, or from the boiler slag using magnetic separation. Although sulfate is not shown in the table, it is usually very low, less than 1.0%, unless pyrites have not been removed from the bottom ash or boiler slag.

If boiler slag has low pH and salt contents, it could exhibit corrosive properties. pH value, electrical resistivity, soluble chloride content, and soluble sulfate content are normally used to evaluate the corrosivity of bottom ash or slag. If the pH value exceeds 5.5, the electrical resistivity is greater than 1500 ohm-centimeters, the soluble chloride content is less than 200 ppm, or the soluble sulfate content is less than 1000 ppm, the slag is judged to be noncorrosive (Chesner et al., 1998; Ramme & Tharaniyil, 2013).

Boiler slag particles are hard and durable with a resistance to surface wear. This material exhibits less abrasion and soundness loss than bottom ash as a result of its glassy surface texture and lower porosity.

Boiler slag is generally a durable material of uniform size within a range of 5.0–0.5 mm (No. 4–No. 35 sieve) that can be blended with other fine aggregates to meet gradation requirements. Normally, boiler slag particles have a smooth texture, but if gases are trapped in the slag as it is tapped from the furnace, the quenched slag will become somewhat vesicular or porous. Boiler slag from the burning of lignite or subbituminous coal tends to be more porous than that of the bituminous coals. Compared to natural granular materials, the maximum dry density values of boiler slag are from 10% to 25% lower, while the optimum moisture content values are higher (Ramme & Tharaniyil, 2013). Table 4.4 gives the gradation of boiler slag.

Table 4.4 Gradation of boiler slag

Size	19 mm ¾″	9.5 mm ⅜″	4.75 mm #4	2.36 mm #8	1.18 mm #16	0.60 mm #30	0.30 mm #50	0.15 mm #100	0.075 mm #200
Percentage passing	100	97–100	90–97	62–85	16–46	4–23	2–12	1–6	0.4–4

Data from Chesner, W.H., Collins, R. J., & MacKay, M.H. (1998). *User guidelines for waste and byproduct materials in pavement construction*. FHWA-RD-97-148. Washington, DC: FHWA; Ramme, B.W., & Tharaniyil, M.P. (2013). *Coal combustion products utilization handbook*, 3rd ed. Milwaukee, WI: We Energies.

Boiler slag is essentially a coarse to medium sand in terms of its particle size with 90–100% passing a 4.75 mm (No. 4) sieve, 40–60% passing a 2.0 mm (No. 10) sieve, 10% or less passing a 0.42 mm (No. 40) sieve, and 5% or less passing a 0.075 mm (No. 200) sieve.

Boiler slag is comparable in specific gravity with lower absorption than limestone sand. The specific gravity of boiler slag usually ranges from 2.3 to 2.9, with dry unit weights ranging from 960 to 1440 kg/m^3 (60 to 90 lb cf).

It should be noted that after size reduction, bottom ash can be screened to produce different size ranges, if desired. The coarse fraction is often also called "boiler slag," which is different from the wet-bottom process and the WBBS product. This boiler slag is more uniformly graded and usually does not require any further screening prior to use.

4.4 Incinerator slag

Incinerator ash and slag are the residues generated from the incinerating of MSW. In general, MSW is defined as the solid waste generated at residences, commercial establishments, and institutions. Most definitions of MSW do not include construction and demolition debris, automobile scrap, industrial wastes, agricultural wastes, medical waste, radioactive waste, and sewage sludge (Chandler et al., 1997).

Major MSWs include, in the order of quantities generated in the United States, paper and paperboard, plastics, ferrous and nonferrous metals, wood, textiles, rubber, and leather. Other wastes include food waste, yard trimmings, and miscellaneous inorganic wastes. The quantities of waste discarded are growing worldwide. More than 1.2 billion tonnes (1.32 billion tons) of MSW was generated in 2012. This will grow to 2.2 billion tonnes (2.42 billion tons) by 2025 (Vergara & Tchobanoglous, 2012; WMW, 2015). On the other hand, the world is more urbanized and urban population is growing. In 2005, there were 2.9 billion urban residents who generated approximately 0.64 kg (1.4 lb) of MSW per person per day (0.68 billion tonnes (0.75 billion tons) per year). In 2015 these amounts increased to approximately three billion residents generating 1.2 kg (2.6 lb) per person per day (1.3 billion tonnes (1.43 billion tons) per year) (World Bank, 2015). In the United States, the total generated and discarded MSW is gradually growing, although the recycling rates have been increasing since the 1980s. Table 4.5 summarizes the generation of MSW in the United States in 1980, 2000, and 2012.

Table 4.5 The trend of generation of municipal solid waste in the United States

Year	MSW generated (1000 tonnes)	MSW recycled (%)	MSW discarded (1000 tonnes)
1980	138,000	22.3	30,770
2000	221,540	58.2	128,940
2012	228,310	72.2	164,840

Data from Environmental Protection Agency (EPA). (2014). *Municipal solid waste generation, recycling, and disposal in the United States*. US Environmental Protection Agency, Office of Resource Conservation and Recovery, February 2014.

China surpassed the United States as the world's largest waste generator in 2004; by 2030 the country will likely produce twice as much MSW as the United States (World Bank, 2015).

Incineration is one of the technologies to manage the increasing MSW. Incineration is the controlled burning of waste at a high temperature. Incinerators are designed to attain complete combustion of wastes. Incineration of MSW does not completely eliminate, but does significantly reduce, the volume of waste to be landfilled. By-products from incineration include ash, slag, air emissions (NO_x, CO, CO_2, SO_2, PM, dioxins, furans, and others), heat, and energy. Modern incinerators are designed to have pollution controls that can lower the pollutant emissions to acceptable levels. Cyclones, electrostatic precipitators, and fabric filters are equipped to remove particulate matter from the flue gas. Scrubbers remove acid gases; catalytic reduction and temperature control minimize NO_x emissions; and activated carbon removes dioxins, furans, and heavy metals from the flue gas. The appropriateness of incineration as a waste management technology depends on local waste characteristics and public acceptance. For an efficient combustion process, incinerated wastes should have a low moisture content, normally less than 50%, and a high heating value, normally larger than 5 MJ/kg (Vergara & Tchobanoglous, 2012).

MSW incineration can be used to generate energy. While older waste incineration plants emitted high levels of pollutants, new technologies and regulatory changes have significantly reduced this concern. In highly industrialized European countries, waste incineration plants have been used increasingly over the past 50 years, mainly because it has been more difficult to find new sites for landfills in densely populated areas. Waste-to-energy (WTE) technology has been developed and matured. The energy generated by incineration is highly demanded in some countries such as Denmark and Sweden. In 2005 it was estimated that 4.8% of the electricity consumed in Denmark was produced by incineration and the amount of heat was approximately 13.7% of the total. Other than Denmark and Sweden, many European countries are recovering heat and electricity from waste. EPA regulations in 1995 and 2000 under the Clean Air Act have succeeded in reducing emissions of dioxins from WTE facilities by more than 99% below 1990 levels, while mercury emissions have been cut by over 90%. The EPA noted these improvements in 2003, citing WTE as a power source "with less environmental impact than almost any other source of electricity." Fig. 4.4 presents a flowchart of MSW treatment.

4.4.1 MSW incineration and incinerator slag formation

Mass burning incineration is used to handle municipal waste without pretreatment on an as-received basis. Mass burning technologies are generally applied for large-scale incineration of mixed or source-separated MSW. Several types of mass burning incineration technologies have been developed after fixed grate, a comparatively old facility, was used. These include movable grate, fluidized bed incineration, and rotary kilns.

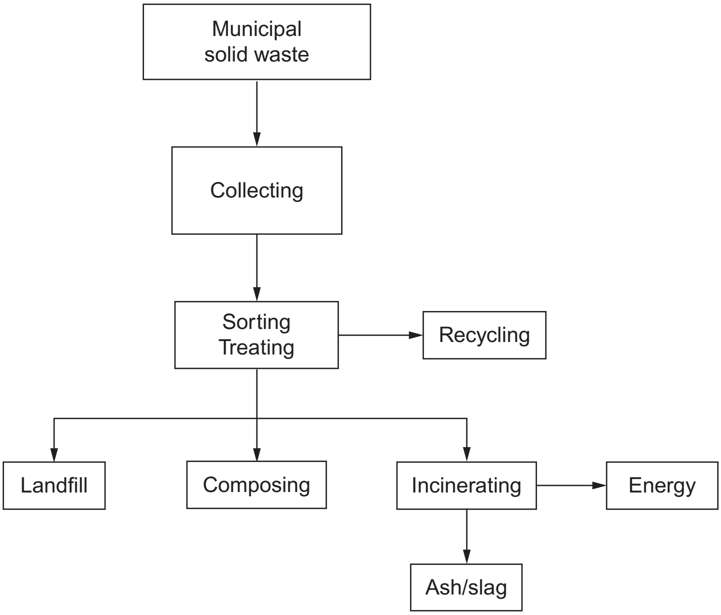

Fig. 4.4 Flowchart of municipal solids waste treatment.

4.4.1.1 Movable grate

The movable (moving) grate has been successfully used for decades. It has been developed and improved to comply with the latest technical and environmental standards. This grate is capable for hauling waste from a combustion chamber to give way for complete and effective combustion. A single such plant is capable for taking in 35 tonnes (38.5 tons) of waste per hour for treatment. Moving grates are more precisely known as *incinerators of municipal solid waste*.

The waste is poured in the grate with the help of a crane from and opening or throat. From here, the waste has to move toward the ash pit. Waste is further treated and water locks wash out ash from it. Air is then flown through the waste and this blown air works to cool down the grate. Some of the grates are cooled with the help of water.

4.4.1.2 Fluidized bed

In this type of incineration, air is blown at high speed over a sand bed. The air gets going through the bed when a point comes where sand granules separate and let air pass through them; then comes the part of mixing and churning. The sand along with the pretreated fuel or waste is kept suspended and is pumped through the air currents. The bed is thus mixed violently and is uptight while small inert particles are kept suspended in air in a fluid-like form. This lets the volume of the waste, sand, and fuel be circulated throughout the furnace, completely. The heat that is produced by an incinerator can be used for generating steam, which is used for driving a turbine to produce electricity. The typical amount produced by municipal waste per tonne is 0.7 MWh for electricity and 2.2 MWh for heating.

The slag is removed from the rear end of the grate by gravity, and normally falls into a water bath, which cools the slag. Some of the water evaporates and must be replaced by fresh water to maintain the water level in the deslagger. Thus, it is possible to operate this removal process in such a way that there is no wastewater stream. It may, however, be advantageous to wash the slag with more water, as this may dissolve and remove some of the salt. The spent water may then be used in a medium or advanced flue gas treatment process (World Bank, 1999).

4.4.1.3 Rotary kiln

Industries and municipalities generally use this type of incinerator for waste treatment. Rotary kiln incineration plants are mostly used for MSW, and also special types of waste unsuitable for burning on a grate, such as various types of hazardous, liquid, and infectious waste.

The rotary kiln is a versatile incineration system and is used to burn solid waste in a variety of containerized, bulk, granular, and other physical forms. Rotary kilns are also used for slurries, sludge, and pastes. This incinerator consists of two chambers: primary and secondary chamber. The system is operated at temperature from 800 to 1650 °C (1472–3002 °F) such that the residues range from dry, free-flowing material to liquid slag. The system can have heat release rates up to 30 million kcal/h, but 15 million kcal/h is a common rate. Volumetric heat release rates are generally in the range of 60 to 100 kcal/m^3 (Niessen, 2010).

A basic rotary kiln comprises a cylindrical, refractory-lined steel shell, supported on two or more trunnions. Kilns are typically from 2.1 to 3.7 m (7–12 ft) in inner diameter and 7.5 to 20 m (25–66 ft) in length. Typically, the kiln shell is augmented by a heavy steel “tire” at the point of support. The kiln may be driven by a powered trunnion roller, by a gear mounted external to the kiln, or by a chain driving a large, circumferential sprocket. The kiln is sloped gently, usually from 0.0 to 0.03 m/m, and rotated slowly at 0.5–3.0 rpm. Usually, the rotational rate is less than 2 rpm but many facilities have the capacity to operate between 1 and 5 rpm. The internal surface of the kiln may be smooth or may contain longitudinal plates or ridges (flights) to lift and spill the material, circumferential ridges (dams) to hold back material, and/or a multitude of festooned chains or baffles (internals) designed to improve the contact of the solid, with the air or flue gas flowing through the kiln (Niessen, 2010).

A kiln may be operated in the concurrent, parallel, or countercurrent mode with respect to the relative direction of gas and solids flow. Generally, concurrent flow is used primarily for wastes with higher heats of combustion and relatively low moisture content. Countercurrent mode operations are primarily for waste with high moisture content, higher than 30%, and for waste with a low heat of combustion. Rotary kilns operated in the countercurrent mode maximize heat and mass transfer. They have a distinct “cold end” where the solids are charged. As the preheating of the solids withdraws heat from the gases, the exiting gases are considerably colder than that in the firing zone where preheated solids and burning fuels combine. Also, as the freshly fed solids are, as yet, unburned, there is the potential for distilling/evaporating organic matter from the waste into an environment with a temperature that is below the combustion threshold. As a consequence, combustion may have to be rekindled through fuel (or "hot" waste) burning in the secondary chamber. Clearly, this situation also emphasizes the importance of achieving good mixing in the secondary chamber (Niessen, 2010).

The mean residence time of material through a kiln may be estimated using the equation

$$\theta = \frac{0.19Lt}{NDS}$$

where θ is the mean residence time (min), Lt is the length of the kiln (m), N is the kiln rotational velocity (rpm), D is the kiln inner diameter (m), and S is the kiln slope (m/m). The length-to-diameter (L/D) ratio of units range from 2:1 to 10:1, with most being found with an L/D between 2.5 and 4.0. Particularly, long kilns are used, most especially with high-moisture wastes, high-fixed-carbon-content waste, or low-heat-of-combustion waste. The loading of the kiln as measured by the volumetric holding rate (Φ) expressed as a percentage of the total kiln volume occupied by the waste and is kept below 20%. In ashing kilns, as indicated below, the load usually takes up 7.5% to 15% (10% is typical), whereas in slagging kilns, 4% to 6% is common. The holding rate is defined as

$$\Phi = 100F\theta / V$$

where Φ is the holding rate (%), F is the waste throughput (m^3/min), θ is the residence time (min) of the solid waste, and V is the kiln volume (m^3) (Niessen, 2010).

A rotary kiln can be categorized into two types based on the final materials generated: an ashing kiln and a slagging kiln. An ashing kiln is a rotatory kiln operated in the ashing mode (with a "dry," nonmolten residue), which is the most common and well-proven system for the incineration of hazardous solid waste. In slagging kilns, as the operating temperature in a kiln increases, one reaches a point where the solid residuals fuse to a molten slag. The ashing mode is most appropriate when the feedstock is of low heat content as, for example, in the remediation of contaminated soils.

At operating temperatures in the 980 °C (1796 °F) range, a high-fired, super duty fire clay refractory is normal, which minimizes reactions and maximizes service life. For higher kiln temperatures (1150–1370 °C; 2102–2912 °F), 60% to 70% alumina brick is normal to minimize the impact of alkali fluxing and attack by iron oxides. At still higher temperature (1480–1600 °C; 2696–2912 °F), solid solution bonded alumina–chromic oxide compositions have been suggested to cope with the Fe_2O_3 reactions. Note that the freedom from significant iron concentrations in the secondary chamber reduces the necessity of the costly alumina–chromic oxide materials. Control of slag composition is usually feasible in industrial kiln operations but much less so in incineration situations. Therefore the operator seldom knows the slag composition, and is unable to influence it; he must rely on his experience with the wastes being fired.

The slag formed after burn off of the organic fraction of the industrial wastes is primarily made up of inorganic oxides; most commonly silica, alumina, iron oxides(s), and lime. In forming low-leaching slags, one wishes to build strong chains within in the slag matrix. Silica, alumina, Fe_2O_3, and other acidic oxides contribute to this characteristic. Basic oxides, including the oxides of the alkali metals (Na_2O and K_2O), and lime (CaO) and sulfide and chloride anions are "chain breaks." They contribute to the sensitivity of the slag to weathering and its tendency to fail leaching tests.

The major solid waste product stream from incineration is the slag, which is sometimes interchangeably called *bottom ash* or *clinker*. It amounts to 20–25% by weight of the waste combusted (or more, if there is a high amount of ash or other noncombustible material in the waste), but only to 5–10% by volume. The main disposal method of the residues from MSWI is landfilling. The slag may either be landfilled as it is or pretreated in one of a number of ways, depending on the requirements and the degree of environmental control measures taken at the landfill. Pretreatment could be done through the washing process or various sorting processes. It is possible to use magnets to recover the iron content of the slag, which may be sold or delivered to a steelworks. A sieving process can recover a gravel size fraction, which may be used as a road base material. Recovery and use of these fractions reduce the amount to be landfilled and, thus, require less landfill capacity. Normally, however, utilization possibilities develop slowly, and it is advisable to have a landfill capacity corresponding to the total slag quantity available before commissioning a new incineration plant. When placing or using the slag in the natural environment it is, of course, important to prevent it from polluting water bodies like ground or surface water reservoirs. Thus, its leaching properties and especially the salt content must be considered (World Bank, 1999).

4.4.2 Basic properties of incinerator slag

The main components of MSWI slag are metals, glass, and mineral constituents of the waste, but some salts, particularly sodium chloride (NaCl), may also be found. Ideally, the loss of ignition (LOI) at 550 °C (1022 °F) of the slag should be zero, but depending on the combustion conditions (eg, grate length and waste-loading factor), LOIs of 2–5% by weight are common. The LOI is mainly incompletely burned organic material. The grain size distribution of the slag ranges from about 1 mm (No. 18) to the largest waste components (such as discarded refrigerators), which can be fed into the furnace (World Bank, 1999).

The chemical composition of MSWI slag is to a great extent determined by the composition of the input MSW and the quality of the various stages of the incinerating process. The chemical composition of incinerator ash/slag is reported by researchers as summarized in Table 4.6.

In Table 4.6, the results from Group 1 are based on 25 incinerator slags sample (Niessen, 2010). The results from Group 2 are based on the mixed incinerator ash and slag (Müller & Rübner, 2006). The results from Group 3 are based on slag prepared by melting MSWI, fly ash at 1400 °C (2552 °F) for 30 min in an electrically heated furnace to obtain slag samples. The samples were water-quenched and further ground in a ball mill (Lin, 2005). The results from Group 4 are based on mixed MSWI ash and slag

Table 4.6 Chemical composition of incinerator ash/slag

Group No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	SO_3	P_2O_5	ZnO	CuO	pH
1	44.73	17.44	9.26	10.52	2.1	8.14	–	–	3.69	1.52	1.54	–	–
2	55.7	14.1	8.8	11.9	2.7	1.4	1.2	–	0.7	–	0.3	0.5	–
3	38.9	23.3	5.3	27.2	3.6	1.2	–	–	–	–	–	–	–
4	14.9–24.5	2.5–5.2	2.0–7.1	9.5–12.8	0.8–1.4	3.0–4.0	0.8–1.3	–	0.2–0.4	0.4–0.8	–	–	–
5	31.07	8.87	11.21	26.44	1.4	2.39	0.92	–	0.09	–	–	–	9.6

Data from Izquierdo, M., Vazquez, E., Querol, X., Barra, M., López, A., & Plana, F. (2001). *Use of bottom ash from municipal solid waste incineration as a road material*. 2001 International Ash Utilization Symposium, Center for Applied Energy Research, university of Kentucky, Paper #37; Lin, K.L. (2005). The influence of municipal solid waste incinerator fly ash slag blended in cement pastes. *Cement and Concrete Research, 35*(2005), 979–986; Lin, K.L., & Lin, D.F. (2006). Hydration characteristics of municipal solid waste incinerator bottom ash slag as a pozzolanic material for use in cement. *Cement and Concrete Research, 28*(2006), 817–823; Müller, U., & Rübner, K. (2006). The microstructure of concrete made with municipal waste incinerator bottom ash as an aggregate component. *Cement and Concrete Research 36*(2006), 1434–1443; Niessen, W.R. (2010). Combustion *and incineration processes*. Boca Raton, FL: CRC.

(Izquierdo et al., 2001). The results from Group 5 are based on slag samples prepared using the same methods in Group 3 (Lin & Lin, 2006). Table 4.7 provides the chemical compositions of different size fractions of coal ash concerning its potential use.

Table 4.7 Chemical properties of MSWI bottom ash concerning its potential use

Component amount in M%	Fraction of MSWI bottom ash		
	2–8 mm	8–16 mm	16–32 mm
Acid soluble chloride	1.59	1.60	1.58
Water soluble chloride	0.49	0.49	0.50
Acid soluble sulfate[a]	0.80	0.48	0.52
Water soluble sulfate[a]	0.03	0.02	0.02
Total sulfate[a]	0.82	0.49	0.55
NaOH sensitive components[b]	3.10	4.17	0.94
Aluminum	1.0	0.7	0.3
Floating components	8.73	5.88	4.97
Organic components[c]	+	−	−
Water solubility	0.75	0.42	0.31
Loss of ignition	1.10	0.94	0.85
Free CaO	3.24	3.24	2.88

[a] Calculated as SO_3.
[b] Glass, Al, Fe, Zn, organic compounds, alkali sensitive mineral phases.
[c] Color in comparison to a colored reference solution (+ = darker, − = lighter)
Data from Müller, U., & Rübner, K. (2006). The microstructure of concrete made with municipal waste incinerator bottom ash as an aggregate component. *Cement and Concrete Research 36*(2006), 1434–1443.

In soluble sulfates in water, some MSWI ash showed up to 1.07%, which exceeded the limit (1%) in some standards (Vegas, Ibanez, San Jose, & Urzelai, 2008). Limited XRD study shows the major minerals in MSWI slag include glassy matrix, quartz, and calcite (Izquierdo et al., 2001).

The absorption of the coarse portion of MSW incinerator ash ranges from 3.5% to 6.2% (Izquierdo et al., 2001). The Los Angeles abrasion test showed the coarse portion of the MSWI ash has a low Los Angeles abrasion result (40–42%), which is lower than the value required for granular base materials (<35%) (Izquierdo et al., 2001; Vegas et al., 2008).

As noted in some of the literature MSWI slag is referred to as the coarse portion of residue from the bottom of the incinerator. The residue from the incinerator can be a well graded between less than 75 μm to 40 mm (No. 200 to 1.6 in.) (Izquierdo et al., 2001; Müller & Rübner, 2006; Vegas et al., 2008).

4.5 Summary

The fused agglomerated materials from phosphorus production, coal combustion, and MSWI are very different in terms of process, original materials, and the properties of slags. Opportunities exist to make use of these valuable mineral resources. The by-products of most concern in the phosphorus production thermal processing steps is phosphorus slag; while the by-product created during the wet processing steps in fertilizer production is phosphogypsum, which is not the focus of this book. Both the by-products phosphogypsum and phosphorus slag are not fully utilized at present.

The utilization rate of CCPs is not high at the present time. The applications include construction industries and civil engineering comprising approximately 32% of all uses, followed by mining applications with 9.9%, and other applications with 1.1%. These percentages are expected to increase, as a result of the development of new uses for CCPs, increased awareness of proven technologies, and a global focus on sustainable development. The fused and then quenched slag is energy invested. There is a potential to activate its hydraulic activity and use as cementitious supplement materials.

Incinerating can lead to significant waste volume reduction and also produces energy in the form of steam or electricity by burning of the solid wastes. MSWI slag and/or ash are more complicated. The term “MSWI slag” has been extensively used. It can refer to (i) the coarse portion of the residues of the incinerators; (ii) a molten material that has undergone higher-temperature incineration; (iii) a molten material that has undergone higher-temperature incineration and then quenched by material made from cool incinerator ash. When discuss the MSWI slag or ash, it should be understood that we mean the processing conditions, origination, and properties of the materials.

Questions

4.1 What are the principal phosphate process technologies? What types of by-products are generated from the processes?
4.2 Based on the basic chemical, physical, and mechanical properties, what is the potential for phosphorus slag use in construction applications?
4.3 What are the differences between boiler slag and incinerator slag?
4.4 Why are the chemical compositions of boiler slag and bottom ash from the same type of coal are similar?
4.5 Why do chemical compositions of MSW incinerator slag vary?
4.6 Why attention should be paid to the formation and process of their generation of the boiler slag and MSWI slag?

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Slag processing

5

5.1 Introduction

From the view of primary product production or the material fusion process, slag is a by-product after it is separated from base metal or element in smelting furnaces or discharged from coal-firing boilers or municipal solid waste incinerators. Unlike production of normal primary products (eg, conventional construction materials) such as mineral aggregate and Portland cement, which are produced under carefully controlled conditions meeting technical specifications, slag is generated as a by-product with less consideration about its further use in construction applications. Because of the nature of the primary product production process, considerable compositional and physical variability of slag results. Therefore, processing, including special treating and handling, with appropriate quality control requirements, is an important step to produce quality slag products.

The inherent variation in slag composition, including chemical and mineral properties, can be traced back to the primary production process. In the iron and steel manufacturing process, the chemical compositions of the main raw materials, iron ores, vary based on different deposits and sources. Nowadays, recycled steel scrap becomes a substitute for iron ore, especially in electric arc furnace (EAF) steelmaking, which increases the complexity of the proportion of the raw materials. On the other hand, the chemical and physical properties of fluxing materials, including burnt lime, dolomitic lime, limestone, and fluorspar, affect the properties of slag significantly. The source and supply changes also affect the properties of slag produced from each individual manufacturer. For example, in the iron- and steelmaking industry, the needs for and production of raw materials are increasing; miners are facing increasing challenges. Many advanced countries that previously relied on low-cost resources from developing countries are finding it increasingly important to revisit their policies on raw materials. The United States, the European Union, some other member states of the Organization for Economic Cooperation and Development (OECD), Japan, and China, have faced the new situation caused by increased competition for raw materials and reduced security of supply (OECD, 2012). All these changes may alter the refining process and particularly the properties of slags, which creates a great challenge that engineers and researchers have to face.

Therefore, it is clear that to convert slag from a by-product to a useful and quality product for selective applications, processing with stringent quality control procedures is vital to lead to rational utilizations. The processing strategies include those generally used for all types of slag, including cooling, mechanical crushing, and screening, and special treating for specific slags.

Pertinent and precise measurement and evaluation of slag properties form the foundation for selecting and developing practicable methods to process and treat slag, and for establishing usability criteria to correctly utilize slag. During processing and treating,

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the chemical, mineral, and physical properties of slag can be modified as designated, and controlled within required limits for the end use in construction. For example, the density, porosity, and the morphology of minerals of slag can be changed by the cooling regime; the particle size of slag can be changed and controlled by cooling rates and mechanical handling. Slag products with various particle sizes and gradation for various uses can be produced by crushing and screening. From special treatment, some unwanted substance(s) existing in slag can be eliminated or partially removed. An example is that the hydration of free lime (f-CaO) in steel slag and some other nonferrous slags, which can cause volumetric instability, can be accelerated and assimilated in a special treating process. Cooling and processing methods can make changes to slag physically and mineralogically and make different slag products for various applications. An example is that iron blast furnace slag can be processed to air-cooled, granulated, expanded, and pelletized slag by using different cooling methods. The resulting products can be used as aggregate in selective applications, cementitious materials, and as functional materials, and skid-resistant material for pavement surfaces, for instance.

With the sustainability considerations in natural resources, the natural environment, and the local economy, the metallurgical industry, especially the steel industry, has adopted a “reduce, reuse, and recycle” (3 R’s) philosophy. The discharge of slag has been more efficiently and effectively managed during the entire process of primary product production. The industry has taken up innovative measures and continues to take further action to fully process, treat, and utilize slag with the ultimate objective of improving the operational efficiency, environment, and economics of the industry. During this transition, the industry has been working to ensure that the fluxing materials and smelting practices are compatible with making low-volume expansion slag aggregate, performance-based testing means are used to measure the volume expansion of the steel slag and some other slag aggregate, and total quality management is implemented to cover all aspects of slag processing to ensure slag products of suitable quality are delivered to the end user. During the last couple of decades, the industry has dramatically reduced the need for raw materials. For example, in the 1970s and 1980s, modern steel plants needed an average of 1.44 tonnes of raw materials to produce 1 tonne of steel. With technology improvements and better planning, the steel industry today uses only 1.15 tonnes of inputs to make 1 tonne of steel. New technologies developed have economically converted slag from what used to be called “waste” in primary material production into various conventional and nonconventional commercial products and wealth-creating new business opportunities.

To be aligned with the philosophy of sustainability, the traditional methods of processing slag have undergone innovations including pretreatment, posttreatment, mechanical handling, and chemical treatment during the production of base metals or in the molten stage before cooling. Slag can be treated in its molten state during production, for example, by using a synthetic fluxing material containing alumina (CAMflux) during steelmaking. By this method, steel slag demonstrated not only volumetric stability but also hydraulic activity, which makes it possible for it to be used as an aggregate and cementitious material (Conjeaud, George, & Sorrentino, 1981; George & Sorrentino, 1982). Another method to treat basic oxygen furnace (BOF) molten slag is adding sand (SiO_2) to lower the basicity and free lime content

(Kühn, Drissen, & Geiseler, 1997). For posttreatment, the hydration of free lime in steel slag can be accelerated by pressure steam treating to reduce the aging time to 2h (Morishita, Kiode, & Komai, 1997). Research and trail production have been conducted in the last 20 years for dry granulation of molten slag (Xie & Jahanshahi, 2008; Xie, Jahanshahi, & Norgate, 2010). In this process slag is quenched and solidified quickly by using air rather than water. Other physical properties of slag can also be modified by pretreatment of molten slag. Liapis and Papayianni (2015) conducted research to lower the specific gravity of EAF slag by adding minerals.

As indicated, both mineral and physical properties of solidified slag can be modified through pretreatment and/or posttreatment to meet the requirements of end products. These properties may include crystallization, vitrification, content of free CaO (f-CaO), free MgO (f-MgO, or f-MgO), volume stability, bulk density, shape, strength, water absorption, and so on. For example, research has found that the ratios of contents of CaO, SiO_2, and Fe_2O_3 to their corresponding molecular weights are related to expansion rate. If the value "*A*" is below a certain value, 3.0 and 3.5 for slow cooling and fast cooling, respectively, the hydration of lime will not happen (Wang, 1986). Consequently, to improve the expansive characteristics of slag, those ratios can be modified within allowable limits.

$$A = \frac{\dfrac{\mathrm{CaO\%}}{\mathrm{M.W.of\,CaO}}}{\dfrac{\mathrm{SiO_2\%}}{\mathrm{M.W.of\,SiO_2}} - \dfrac{\mathrm{Fe_2O_3\%}}{\mathrm{M.W.of\,Fe_2O_3}}}$$

Fig. 5.1 presents the loop from slag generation through to its end utilization. This loop includes processing and special treatment; laboratory testing and performance-based utilization criteria establishment; the end use; performance evaluation; and the modification of usability criteria, processing, and testing methods.

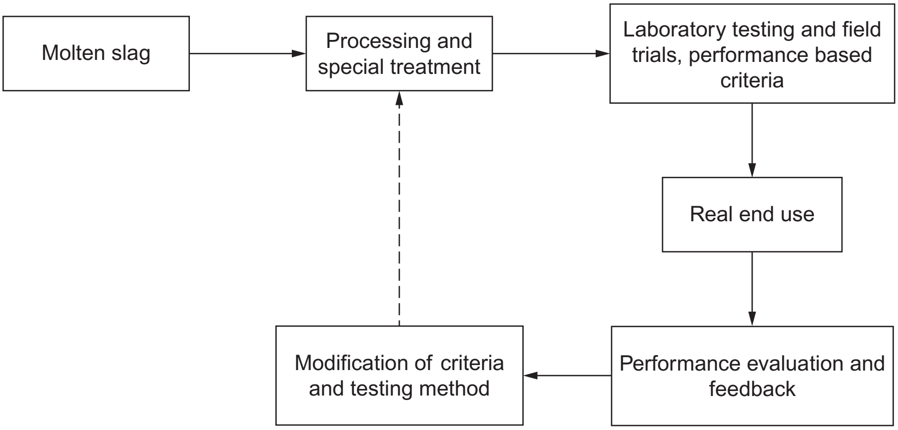

Fig. 5.1 The technical loop of the utilization of slag.

5.2 Evaluation of slag and slag products

For the practicable use of slag in construction applications, the benefits derived from the utilization include engineering, environmental, and economic aspects. If the end product is technically sound, environmentally acceptable, and economically viable, the benefits will exist simultaneously and there will be a potential for the use of the slag. This is depicted in Fig. 5.2. The intersected area represents the greatest potential for the use of slag. To open an avenue for a rational use of a specific slag, establishing a relationship between the properties of slag, including chemical, mineral, physical, and any potentially "negative" properties, and the required properties of the end product is important. This relationship involves both engineering and environmental aspects. It is a guarantor for rational, safe, and successful use. An ideal relationship should be quantitative. A quantitative relationship is the key to ensure long-term utilization of a slag, and to steadily transfer a slag into a coproduct sustainably.

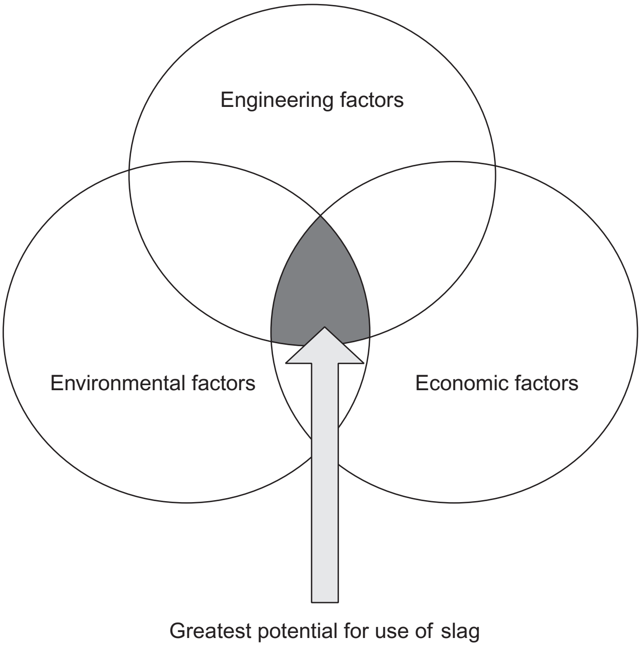

Fig. 5.2 The greatest potential of slag utilization.

To establish the relationship between a slag and the end product incorporating the slag, the evaluation methodology used to describe the intrinsic characteristics of the slag and the end product plays an important role. The objects of the evaluation include both slag and end product and samples obtained from the site and those prepared in the laboratory. The results from performance-based or performance-related evaluation from the end products should be continuously monitored and tested in both the short- and long-term. The evaluation results should provide references to further modifying the test methods and slag processing methods employed, and the intrinsic relationship established.

5.2.1 Inherent variation of slag properties and performance requirements

As indicated in Section 5.1, high variation of chemical and physical characteristics of slag due to varied sources of raw materials and process technologies in the primary product production and the lack of quantitative relationships (criteria) between the intrinsic properties of slag and the required properties of end products have hindered the comprehensive utilization of slag.

The fluctuation of chemical composition of slag exist is twofold. First, there is a comparatively wider range of a single substance in a given slag sample; that is, for a given slag, the content of an oxide can fluctuate within a very wide range. Second, there is a variation of composition and content among slags from different processes and sources, which means a substance(s) existing in one slag may not exit in another one and the content may vary. This reflects that each technology of metallurgy and its slag production is specific and the properties of each slag are unique. Even for the same type of slag from different sources or manufacturers, the properties, especially the chemical compositions, can be different.

As for end products or final utilization, there has been a full range of proven construction applications for ferrous, nonferrous, and nonmetallurgical slags, iron, steel, copper, nickel, and phosphorus slags, for instance, from aggregate through to cementitious materials. These applications involve different materials and have different performance requirements. Specific evaluation methods for each individual use are required. Performance-based or performance-related evaluation, including special testing methods and criteria for utilization, should be developed and used along with the intrinsic characteristics of slag itself. For example, phosphorus slag contains trace amounts of radioactive substances. To safely use it, the radioactive value of the slag should be controlled within a certain limit; for instance, in picocuries per gram (pCi/g). In the United States and Europe, these values are currently 10 and 13 pCi/g, respectively. However, from a performance of end product and final utilization point of view, the actual exposure from the end product (ie, where, when, and how it is to be used) and performance-based characteristics of the end product should be considered and given a higher priority.

Another example is the free lime content limit set for slag. Research has found that the dominant factor contributing to the volumetric expansion of slag, mainly steel slag, is free lime along with periclase (free MgO). The total content of free lime in a slag is to be considered a criterion for evaluation of volumetric expansion characteristics of a slag and for suitable use of a slag. Varied upper limits of free lime contents have been suggested by researchers for different uses. However, as far as volumetric stability is concerned, it usually refers to the end product or the final composite material under designated environment and conditions in use, rather than its constituent materials. It is therefore desirable, based on chemical, mineral, and physical characteristics, to establish performance-based criteria to reflect the stability or performance of end product under actual conditions, and to select applicable limits for a given end use. The end products' performance and requirements should be considered. In particular, a free lime limit for unbound base and subbase materials may not be suitable for slag aggregate in constrained conditions. Therefore, free lime limits set for these uses should be different.

Test methodology is an effective tool in the evaluation of slag, slag products, and end products. Test methods should reflect the unique nature and ultimate performance of slag, slag product, and end products. For example, to determine the free lime content in steel slag, the method used for Portland cement is not appropriate because the cement has not undergone hydration before use and slag has experienced hydration during cooling, stockpiling, and/or aging. The hydrated product ($Ca(OH)_2$), for instance, should be subtracted. For example, using volumetric chemical analysis methods combined with differential thermal analysis (DTA) methods for determination of f-CaO are effective to provide actual unhydrated lime content. Various physical tests—autoclave testing, for instance—is necessary as a supplementary assessment tool.

In the evaluation of a slag, comparison study is important. Same slag samples with and without undergoing special treating should be examined to assess the effectiveness of the treating methods used. The evaluation should include comparison of chemical and mineral changes and physical stability by means of various testing methods. The properties of raw materials used in the primary product production should also be analyzed to draw any correlations between the raw materials and slag.

Furthermore, in addition to the characteristics of slag itself, the end product's physical and mechanical properties are more important in determination of the usability of a specific slag. It has been shown in the laboratory and in construction, that air-cooled, modified nonferrous slags are an excellent aggregate in granular base, engineered fill, and hot-mix asphalt. There is significant potential for ground granulated copper and nickel slags as supplementary cementitious materials that are being developed as high-ratio addition uses. Successful utilization of a particular slag mainly depends on its chemical and mineral properties, and more importantly, from which the physical and mechanical characteristics resulted. This will be further discussed in the following chapters.

5.2.2 Evaluation methodology

To be used in construction applications, slag products must possess a sufficient volumetrically stable nature to ensure the stability of the end product. However, as indicated, f-CaO and periclase in some slags, particularly steel slag, may cause slag volume expansion before effective treating. In contact with water unhydrated lime and magnesium react to form hydroxides with increased volume. Depending on the hydration rate and the content of f-CaO lime and periclase, this reaction causes a volume increase of a slag mostly combined with a disintegration of slag pieces and loss of strength. Therefore, volume expansion of slag is a problem that must be controlled before it can be used in construction. For actual slag samples, free lime contents can fluctuate from less than 0.1% to over 10% in the same type of slag. This indicates the importance of testing, evaluation, and establishment of the usability criteria. Some substances in slag may cause environmental concerns (Proctor et al., 2000) that can be dealt with by proper treating and selective utilization. Environmental aspects of slag utilization will be discussed in Chapter 7.

Laboratory test methods have been developed to determine and measure the properties of slag, especially the expansion properties of steel slag, which are briefly described below.

5.2.2.1 Volume expansion test

The volume expansion test has been used in several countries since the 1970s, including Canada, the United States, and Japan (Emery, 1977; JSA, 1986; PennDOT, 1978). It has been an American Society for Testing and Materials (ASTM) standard since the 1980s. The current version is ASTM 4792—Standard Test Method for Potential Expansion of Aggregate from Hydration Reactions (ASTM, 2013). The procedure involves preparing slag specimens under nonexpansive control conditions using a stainless steel mold with perforated base plates to allow for moisture movement during the immersion period. The specimens are totally immersed in a hot water bath and the expansion with time is monitored. The temperature of the water bath is maintained constant throughout the test. Actual temperature ranges can be adjusted from 73°C to 82°C.

5.2.2.2 Powdering ratio test

The powdering ratio test was originally developed to evaluate steel slag stability in Japan. In this method, the portion of a steel slag sample retained on a 4.75 mm (No. 4) sieve is treated under thermal or autoclave conditions continuously until the powdering ratio becomes invariable. The ratio of the mass of the sample after treating passing 0.30 (No. 50) and 4.75 mm sieves to the total mass of the sample before treating is defined as powdering ratios T_1 and T_2. The results from the test is generally well correlated with free lime content in steel slag. However, the method neglects cracked particles larger than 0.3 or 4.75 mm.

The test procedure of the test includes (i) remove the material passing a 4.75 mm sieve from the sample; (ii) weigh the remainder (ie, material retained at a 4.75 mm sieve); (iii) treat the sample under autoclaving or saturated steam condition; (iv) dry and weigh the materials passing the 0.30 mm sieve and 4.75 mm sieve; (v) repeat steps (iii) and (iv) until constant mass is attained; (vi) calculate the ratios of mass passing 0.30 and 4.75 mm sieves to the total mass of the sample to obtain T_1 and T_2.

The powdering can explain the volume stability of steel slag from three aspects: (i) evaluation and comparison of stability properties of different steel slags under a given condition; (ii) evaluation of the effectiveness of certain treating methods on stability of steel slag; and (iii) determination of the treating time and treating condition needed for a particular slag. Table 5.1 gives an example of powdering ratio results for two BOF slag samples tested at a pressure of 375 kPa, 137°C (279°F), for 400 min when the powdering ratios reached constant values.

Table 5.1 Comparison of powdering ratios among different BOF slags

Slag sample	f-CaO content (%)	Treating time (min)	T_1 (%)	T_2 (%)
BOF slag 1	1.60	400	1.66	6.02
BOF slag 2	1.08	400	0.85	3.00

Data from Wang, G.C. (1992). *The utilization of steel slag in engineering applications*. PhD thesis. University of Wollongong, Wollongong, NSW, Australia.

Similar tests were conducted on open hearth steel slag samples that had powdering ratios ranging from 45% to 80% under 100°C steam treating.

5.2.2.3 Autoclave disruption test

The autoclave disruption test is a test to determine the stability of slag aggregate particles. In this test, slag samples are separated into several particle size fractions. After visual examination and petrographic analysis, a certain number (eg, 100 or 50) of slag particles from each size fraction are chosen and washed, and then placed into an autoclave to be treated for 1–3 h. The ratio of the number of slag particles cracked, powdered, or containing visually observed cracks after treatment to the total number of slag particles selected is defined as the particle-disruption ratio R. It is generally agreed that autoclave testing can accelerate the hydration of free lime and especially periclase, which has slow hydration rate. Therefore, this test can provide an approximate assessment and indication of long-term stability of slag aggregate particles due to free magnesium and water reaction. This is a simple test and the information provided by the results is useful. The R value is an important factor in evaluating the overall stability of slag aggregate in various matrices where slag is incorporated and in developing criteria for usability of slag in constrained conditions.

Table 5.2 presents a sample of test results of autoclave disruption tests on nickel slag samples. The two air-cooled slag samples were divided into four size fractions: passing 19.0 mm (3/4 in.) retained 16 mm (5/8 in.); passing 16 mm retained 13.2 mm (0.52 in.); passing 13.2 mm retained 9.5 mm (3/8 in.); and passing 9.5 mm retained 4.75 mm. From visual examination, 50 particles of good, hard nickel slag are selected for each size fraction. These

Table 5.2 **Autoclave disruption test for air-cooled nickel slag**

Size fraction (mm)	Total number of particles	Number of particles by quality after autoclaving			Disruption ratio (%)
		Good	Fair	Poor	
Sample 1					
19.0–16.0	50	26	24		0
16.0–13.2	50	33	17		0
13.2–9.5	50	47	3		0
9.5–4.75	50	45	5		0
Average	50	38	12		0
Sample 2					
19.0–16.0	50	30	20		0
16.0–13.2	50	39	11		0
13.2–9.5	50	43	7		0
9.5–4.75	50	45	5		0
Average	50	39	11		0
Test average	50	39	12		0

Data from Wang, G., Thompson, R., & Wang, Y. (2011). Hot-mix asphalt that contains nickel slag aggregate—Laboratory evaluation of use in highway construction. *Journal of the Transportation Research Board, 2*(2208), 1–8.

particles are then placed on a piece of filter paper on racks and suspended in a standard pressure cooker containing a couple of liters of water. The pressure cooker is sealed and then the water is heated to boiling at 1 atmosphere pressure. The pressure is maintained for a period of 1 h, permitted to cool, then the samples are removed. Each size fraction is carefully examined visually for signs of deterioration (cracking, disruption, etc.). Particles that do not exhibit any cracking or disruption are considered to be good; particles that partially crack are fair; and particles that completely crack, fail, or soften are considered poor.

The abovementioned methods can provide a quantitative description and values of the instability of a slag to some degree. However, these test methods only provide comparative results between different slag samples. They can neither directly indicate if a slag can be successfully used in an application nor accurately predict the end product characteristics. It is often difficult to ascertain judicious relationships between test results and practical values. Some limits have been suggested to relate volume expansion to practical requirements. For example, for granular road base construction, ≤2.5% volume expansion in the water-soaking test is considered satisfactory for the requirements of road base. Particle-disruption ratio has been proposed as a criterion and a test procedure incorporated in the deduction of a usability criterion for slag use (Wang, Wang, & Gao, 2010).

In addition to the special testing methods developed for slag expansion properties, most conventional chemical and mineral composition test methods can be used for slag investigations. These include (i) X-ray diffraction (XRD) analysis; (ii) scanning electron microscope (SEM) analysis; (iii) energy dispersive X-ray spectroscopy (EDS, EDX, or XEDS); (iv) gamma-ray spectroscopy; (v) DTA; and (vi) autoclave treatment.

5.2.2.4 XRD analysis

XRD analysis can investigate crystalline material structure, including atomic arrangement, crystallite size, and imperfections. Fig. 5.3 shows the results using a Phillips

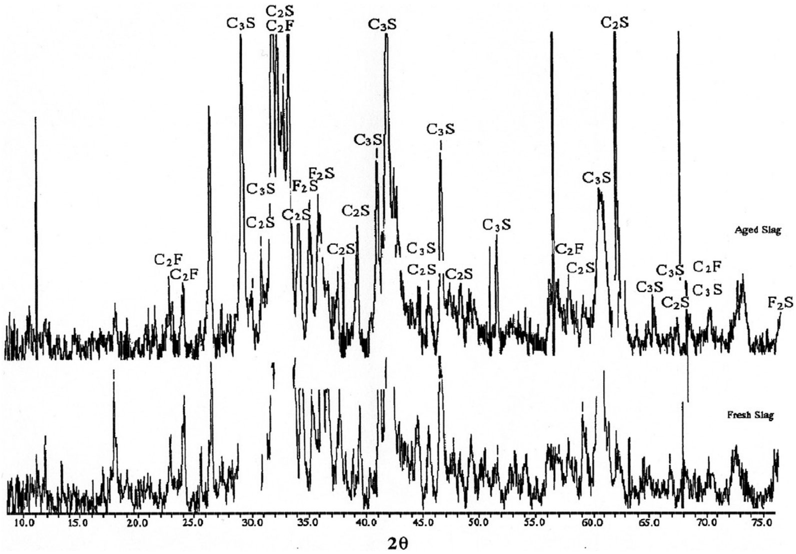

Fig. 5.3 XRD pattern of fresh and aged BOF slag samples.

X-Ray Diffractometer (Model 1130/90), with a graphite monochromator and $\mathrm{CuK}\overline{\alpha}$ radiation, running at a count rate of 10^3. The analysis was carried out on the fresh and aged BOF slag samples after magnetic separation of iron.

In Fig. 5.3, the *d*-spacing value of 35 peaks for aged steel slag and 46 peaks for fresh steel slag are given. Analysis resulted in 28 main peaks being identified, and mineral constituents being $2CaO{\cdot}SiO_2$ (larnite), $3CaO{\cdot}SiO_2$ (alite with some solid solution), $2CaO{\cdot}Fe_2O_3$, and $2FeO{\cdot}SiO_2$.

5.2.2.5 SEM analysis

SEM is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that can be detected and that contain information about the sample's surface topography and composition. Fig. 5.4 presents secondary imaging

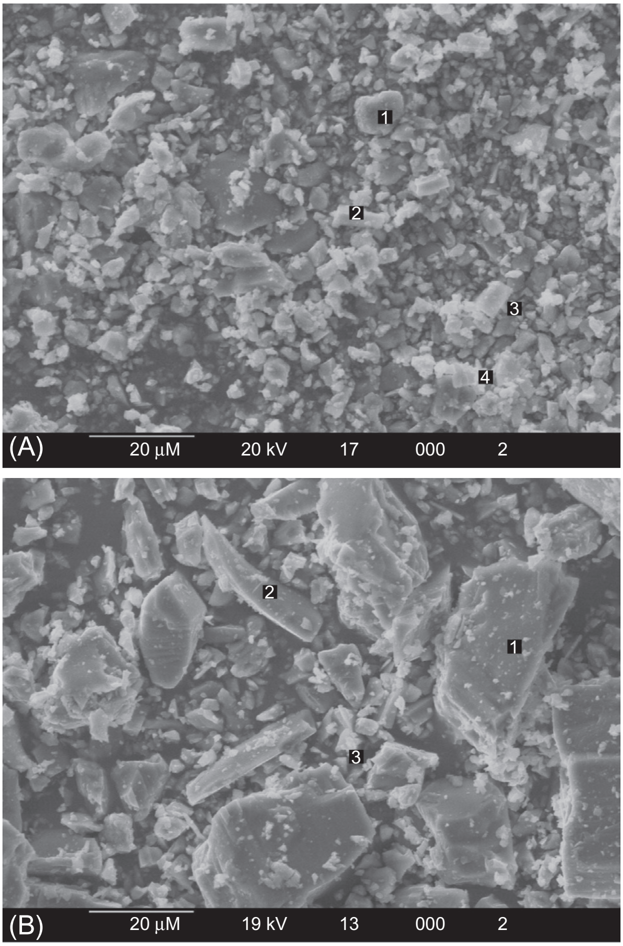

Fig. 5.4 Air-cooled nickel slag samples' secondary imaging by SEM × 1000. (A) Air-cooled. (B) Emergency pit slag.

analysis that was used for observation of FeO, SiO_2, MgO; back-reflection imaging for observation of minerals containing light metals, such as Ni, Co, W in a nickel slag sample. The results of SEM analysis show that the minerals are main block and long strip shaped.

5.2.2.6 EDS analysis

EDS analysis is also called energy dispersive X-ray analysis or energy dispersive X-ray microanalysis. It is an analytical technique used for the elemental analysis or chemical characterization of a sample. It relies on an interaction of some source of X-ray excitation and a sample. Its characterization capabilities are due in large part to the fundamental principle that each element has a unique atomic structure allowing a unique set of peaks on its X-ray emission spectrum. Fig. 5.5 and Table 5.3 give the results of EDS analysis for the cracked surface of a BOF slag particle after autoclave treatment. It can be seen that Ca is the dominant element in the sample, although chloride is also found in the sample.

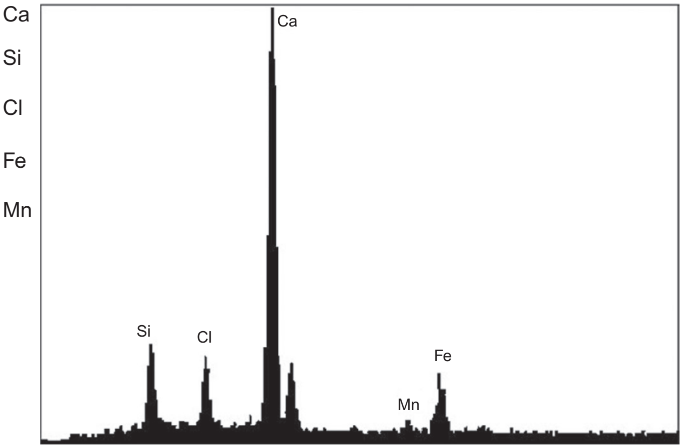

Fig. 5.5 A test result of cracked surface of a BOF slag particle using EDS.

Table 5.3 **EDS analysis result for BOF slag**

Element	Shell	Weight%	Atomic%
Ca	K	60.8899	60.1600
Si	K	12.2610	17.2873
Cl	K	8.5383	9.5369
Fe	K	15.5730	11.0423
Mn	K	2.7376	1.9733

Data from Wang, G.C. (1992). *The utilization of steel slag in engineering applications*. PhD thesis. University of Wollongong, Wollongong, NSW, Australia.

5.2.2.7 Gamma-ray spectroscopy analysis

Gamma-ray spectroscopy analysis is used to determine quantitatively the radioactivity of phosphorus slag. It gives the energy spectra of gamma-ray sources. Most radioactive sources produce gamma rays that are of various energies and intensities. When these emissions are detected and analyzed with a spectroscopy system, a gamma-ray energy spectrum can be produced. A detailed analysis of this spectrum is typically used to determine the identity and quantity of gamma emitters present in a gamma source, and is a vital tool in a radiometric assay. Phosphorus slag and phosphogypsum are typical examples.

5.2.2.8 DTA analysis

DTA analysis is a thermoanalytic technique. In DTA, the slag sample under study and an inert reference are made to undergo identical thermal cycles, while recording any temperature difference between sample and reference; hydrated f-CaO, $Ca(OH)_2$, for instance. The differential temperature is then plotted against time, or against temperature (DTA curve, or thermogram). Changes in the sample, either exothermic or endothermic, can be detected relative to the inert reference. Thus, a DTA curve provides data on the transformations that have occurred, such as glass transitions, crystallization, melting, and sublimation. The area under a DTA peak is the enthalpy change and is not affected by the heat capacity of the sample tested.

5.2.2.9 Autoclave treatment

Autoclave treatment is a pretreating method for slag samples before being put into a special test. An autoclave or pressure cooker can be selected for this test. The saturated steam can be at 100°C (212°F) or at 137°C (279°F) with a pressure of 357 kPa, or higher to 200°C (392°F) (Inoue & Suito, 1995). The samples can be visually observed or tested instrumentally. The heat cycle incorporated can be designed based on the materials and the purpose of the examination.

5.2.2.10 Chemical composition analysis

Various analytical chemistry methods can be used to determine chemical compositions of slag samples. It should be noted that $Ca(OH)_2$ converted from f-CaO hydration during the treating and aging period can affect the free lime content when a volumetric method (glycerol-alcohol) is used. Both f-CaO and $Ca(OH)_2$ can react with glycerin and alcohol. Therefore, a DTA test or other test that can determine the $Ca(OH)_2$ content is suggested to modify the results. The detailed method and chemical reactions are presented in Appendix 3.

5.3 Blast furnace slag processing

Iron blast furnace slag results from the fusion of iron ore, fluxing materials, and coke; the reduction reactions; and the separation of iron from the ore. As indicated in Chapter 2, the term *blast furnace slag* is used often to refer to iron blast furnace slag to distinguish it from other types of blast furnace slag such as copper, lead, and zinc blast furnace slag. Because the blast furnace operation is a continuous process with carefully controlled raw materials being fed in and furnace conditions, among the various slags, iron blast furnace slag is the easiest to deal with technically to use in construction-related applications. Like other slags, although blast furnace slag varies in chemical and mineral composition, its physical structures depend on the method of cooling of the slag and the processing method used. The nature of the minerals formed when slag cools slowly is of concern in the use of the materials as a dense aggregate. It is of less direct interest for slag in the glassy, or granulated form used as an aggregate, but its hydraulic activity is essential in its use as a cementitious material (Murphy, Meadowcroft, & Barr, 1997; Rendón-Angeles et al., 2004).

Liquid blast furnace slag cooling regimes traditionally include air-cooling, granulating (wet), expanding, and pelletizing, and result in four distinct types of blast furnace slag: air-cooled slag, solidified under ambient conditions; granulated slag, solidified by quick water quenching to a vitrified (glassy) state; expanded or foamed slag, solidified with controlled quantities of water, sometimes with air or steam; and pelletizing slag. In terms of quantity produced, granulated slag is the predominant product.

Because of its relatively consistent quality, blast furnace slag is generally covered by conventional specifications for aggregate and cementitious applications. Processed air-cooled blast furnace slag and unground blast furnace slag is generally considered to be a construction aggregate and ground granulated blast furnace slag (GGBFS) is considered a supplementary cementitious material. Fig. 5.6 presents blast furnace slag processing and treating routes.

Typical ferrous slag production statistics for several countries indicates a trend in Europe toward more granulation than in North America, but palletizing and granulating are growing as slag cement manufacture develops. In Europe, approximately 69%

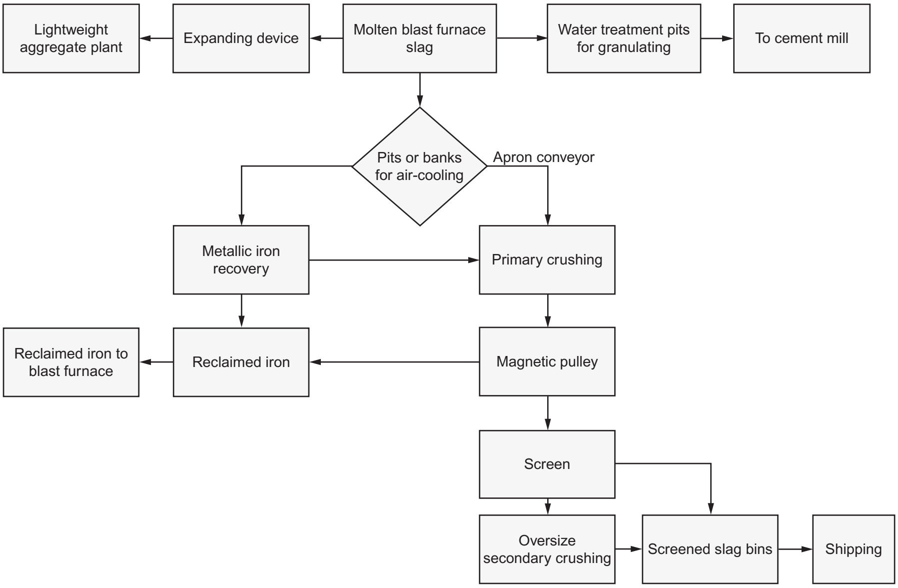

Fig. 5.6 Blast furnace slag processing and treating routes.

of the total blast furnace production was granulated in 2000, with 29% air-cooled, and 2% pelletized (Motz, 2002). In the United States, approximate 69% was air-cooled and 31% was granulated in 2012 (USGS, 2012).

Both the total production and the relation between air-cooled (crystalline) and granulated blast furnace slag (vitrified) have changed significantly in the past. For example, in Germany the slag generation rate in the 1940s amounted to between 900 (1800) and 1000 kg/tonne (2000lb/ton) pig iron. This rate has been decreased to about 250 kg/tonne (500lb/ton) pig iron until now. In some countries this rate is even lower than 200 kg/tonne pig iron. The decline of the slag generation affects the properties of slag, mainly porosity and strength; the higher the porosity the lower the unit weight. This is one of the reasons leading to increased granulated blast furnace slag production and its successful use in cement manufacturing (Motz, 2002).

5.3.1 Air-cooling

Air-cooled slag is solidified under ambient conditions. Immediately after being discharged from the blast furnace, the molten blast furnace slag is dumped into cooling pits for air-cooling before further processing for slag products. When the slag undergoes air-cooling in the pit, stratification of the layers resulting from pouring hot molten slag over partially cooled slag, causes cracking so that upon further cooling it can be readily picked up with power shovels. Water is used in air-cooling to aid fragmentation and to hydrate possibly incomplete fused pieces of fluxing materials that might produce spalls or popouts when slag is used as a concrete aggregate. After cooling to 93°C (200°F) or lower, the slag is transported to a plant for crushing and screening to a size appropriate for concrete use (Dobrowolski, 1998). Air-cooled blast furnace slag has been extensively used as a construction aggregate.

5.3.2 Granulating

Although the history of the use of blast furnace slag can be dated back to as early as 350 BC, it had been basically used as an aggregate material, until the hydraulicity of granulated blast furnace slag was found. Now, granulation is currently one of the dominant treatments of slag, including nonferrous slags, copper, and zinc, for instance.

Granulated slag is solidified by quick water quenching to a glassy or vitreous state, with latent hydraulic properties, and crystallization is largely prevented. This rapid cooling by water results also in fragmentation of the material into a granulated from. GGBFS is mainly used is slag cement manufacture by grinding with Portland cement clinker (Neville, 2012).

In 2002, granulated slag accounted for approximately 70% of the total blast furnace slag production in the world; the proportion of cement containing GGBFS is as high as 80% in some countries (Geiseler & Vaittinen, 2002).

5.3.3 Expanding

Expanded (foamed, or slag pumice) slag is a minor type of blast furnace slag that is solidified with controlled quantities of water. Air and/or steam could be applied to the slag. Expanded slag is normally somewhat porous in nature although it is usually not enough so that it can be classified and used as lightweight aggregate. Expanded slag is produced in two ways. First, a limited amount of water in the form of spray comes into contact with the molten slag when being discharged from the furnace. Steam is generated and it bloats the still plastic slag, so that the slag hardens in a porous form, rather similar to pumice. This is the water-jet process. Second, in the machine process, the molten slag is rapidly agitated with a controlled amount of water. Steam is entrapped and there is also some formation of gases due to chemical reactions of some slag constituents with water vapor. With both these methods, crushing of the expanded slag is required. Although some of the expanded slag finds use in structural lightweight concrete, most of it is used in the manufacture of concrete block (Dobrowolski, 1998).

5.3.4 Pelletizing

Minor blast furnace slag can be pelletized by moderate cooling. Pelletized slag is solidified by water and air quenching in conjunction with a spinning drum. Molten slag containing gas bubbles is projected through a water spray so as to form pellets. These are rounded in shape and have a smooth coated surface. However, crushing (which destroys the coating) has to be used to obtain fine particles. The bulk density of pelletized blast furnace slag is typically 850 kg/m^3 (55 lb cf). Appropriate production control ensures the formation of crystalline material, which is preferable for use as aggregate; this is in contrast to blast furnace slag pellets used in the manufacture of blast furnace cement (Neville, 2012). Experience has shown that the coarser pellets have properties like crystalline slags and the finer pellets like vitrified slags. Subsequent to the relevant heat treatment, crystalline, vitrified, and pelletized slags undergo a mechanical processing to produce different slag products (Motz, 2002).

The pelletizing process was developed in Ontario, Canada, and one of the major types of products in Ontario, Canada (MNRO, 1992). It has been used both as lightweight aggregate and in slag cement manufacture when suitably vitrified.

5.3.5 Dry granulation

Dry granulation of blast furnace slag was experimented with in the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia. In this process, molten slag is atomized under centrifugal forces on a spinning disc and the slag droplets generated are quenched and solidified quickly using air (Xie & Jahanshahi, 2008; Xie et al., 2010). The process produces solid slag granules with added value. In the meantime, high-grade waste heat can be recovered (500–600°C; 932–1112°F for on-site utilization). Compared with conventional wet granulation, the dry granulation process offers a more sustainable approach for processing molten slag through saving water, reducing pollution, as well as recovering water heat to reduce energy consumption, hence greenhouse gas emissions.

The concept for CSIRO's new integrated slag treatment process is based on a two-step operation involving a dry granulator and a packed-bed countercurrent heat exchanger as shown in Fig. 5.7. A disc design was developed to produce fine granulates without the formation of slag wool as shown in Fig. 5.8. A cyclone airflow is employed to quench the hot granules to produce a highly glassy product.

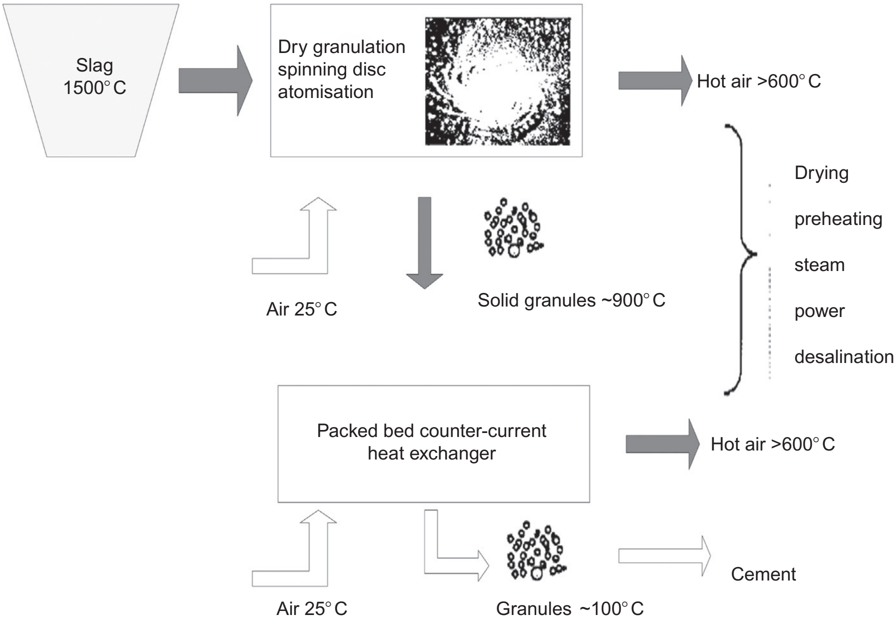

Fig. 5.7 Conceptual process flow sheet for integrated dry granulation and heat recovery. Courtesy of Xie, Jahanshahi, and Norgate of CSIRO.

Fig. 5.8 (A) Still image of slag atomization on a spinning disc (1520°C and 1500 rpm) and (B) solid granules produced.
Courtesy of Xie, Jahanshahi, and Norgate of CSIRO.

5.4 Steel slag processing

The important aspect of utilization of steel slag is proper processing and treating. In BOF and EAF steelmaking processes, BOF slag, EAF slag, ladle slag, scrap, and waste refractories are generated. On the other hand, the fluxing materials and slag practices can affect slag properties, which was experimentally proved by examinations of a steelmaking furnace (Farrand & Emery, 1995). In the investigation, different practices were implemented on a trial basis to assess the effect on steel slag aggregate quality. The results showed the significant difference that flux and slag practice can have on steel slag aggregate volume expansion. One flux practice resulted in slag that was contaminated with lime or dolime and exhibited greater volume expansion as compared with the other one without the same situation as the former. Hence, sorting the materials is very important in each step of processing of slag in the plant.

Various processing and treatment methods have been developed since it was recognized that steel slag can be utilized. New processing and treating strategies have been attributed to the sustainable development of slag utilization and the change in perspective from the steelmaking industry and the general public. Selected processing and treatment methods, including those conducted after slag tapping and pouring or during steelmaking, are presented in the following sections.

5.4.1 Pretreatment

5.4.1.1 Addition of sand

To lower f-CaO content and activity, SiO_2 is used to lower the basicity of steel slag. Thyssen Stahl AG together with the FEhS in Germany developed a treatment process to lower the free lime content of the BOF slag. When molten slag is tapped into a slag pot, sand is injected into liquid slag with oxygen as the carrier gas. By this technique the basicity of the slag is reduced and the free lime content in the slag is bound into stable slag minerals and, consequently, volumetric stability is improved (Kühn et al., 1997).

5.4.1.2 Unit weight modification

High unit weight of certain steel slag hinders its broader applications due to economic reasons, mainly the hauling cost. EAF slag can be treated in its molten state by adding perlite mineral to lower its unit weight. Experiments conducted by Liapis and Papayianni (2015) indicated that the addition of 10% of perlite per weight of slag can decrease unit weight of slag 7.5% compared to molten slag without any additions. The modified slag has no reported volumetric expansion problem.

5.4.1.3 Water quenching

Reddy, Pradhan, and Chandra (2006) conducted an experiment to treat molten BOF slag. The slag was taken into a 400 kg (882 lb) alumina-lined crucible and mixed with 3% fluorspar. Two distinct process routes were followed to treat the BOF slag as shown in Fig. 5.9.

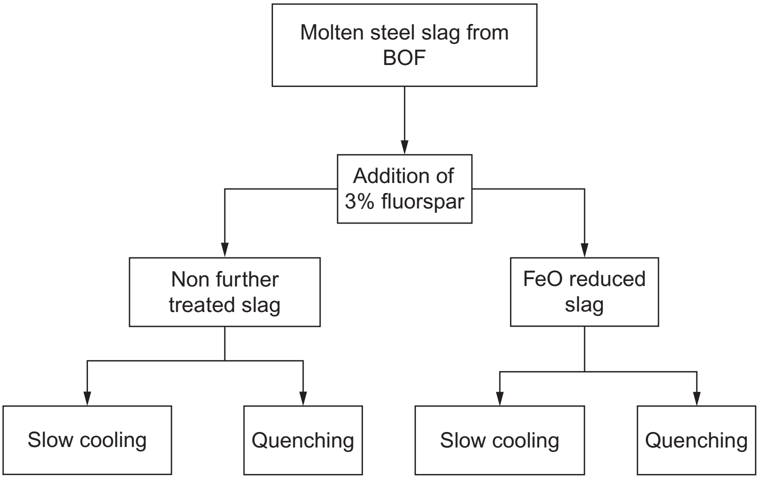

Fig. 5.9 Two distinct process routes for BOF slag treating.

The normal slag at 1500°C (2732°F) was subjected to two different cooling rates. First, it was allowed to cool in the alumina crucible for a prolonged time and, second, it was quenched and granulated with high-pressure water jets. Treated slag was obtained by reducing the FeO and P_2O_5 present in the slag by metallothermic reduction. The recovered metal was separated out from the bottom of the crucible, and the nonmetallic slag from 1350°C (2462°F) was subjected to two different cooling rates in a manner similar to the normal slag. The chemical analysis indicated that treated slag contained less than 1.0% free lime, where normal slag contained ~10% free lime (Reddy et al., 2006).

5.4.1.4 Modify leaching property

Pretreatment can modify for the leaching property of slag. Mombelli et al. (2014) conducted an experiment by adding quartz to EAF slag. The addition of SiO_2 leads to the formation of a gehlenite-type phase that is completely stable and assures safe and inert behavior. Modified slag demonstrated stability in leaching tests.

5.4.1.5 Flux alteration

To prove the effect of flux and the steelmaking process on steel slag, a trial was conducted using a fine mineral jig to process steel slag. The jig used wet gravity separation in an attempt to eliminate the less dense, lime-rich particles from the slag. The resulting materials had a clean washed appearance. However, testing of the aggregate showed volume expansion of 3.9% for the coarse size fraction and 4.5% for the fine. Later investigation showed that this was attributed to the effect of the steelmaking flux practice on the quality of the aggregate. It indicated that the slag processor cannot work in isolation to produce good aggregate if the steelmaker is producing slag contaminated with lime or dolime (Farrand & Emery, 1995).

5.4.2 Posttreatment

5.4.2.1 Crushing and screening

The initial use of steel slag was due to the shortage of aggregate for road construction. To extend the resource of aggregate, steel slag was simply crushed mechanically or manually (Thomas & Strong, 1980). However, due to the general lack of recognition of the importance of properties of steel slag, localized instability occurred in the road due to dimensional changes in the steel slag aggregate. The simple method is rational only for the steel slag with composition containing little or no harmful constituents. Apparently, the usefulness of the method was restricted due to the fluctuation of free lime.

5.4.2.2 Stockpiling and aging

Stockpiling and aging is the traditional method of steel slag treatment. The volume stability of BOF slag is mainly influenced by the free lime content. To guarantee a sufficient volume stability the solid slag has been weathered. During the weathering or aging when slag is stockpiled under free atmosphere, f-CaO will react with moisture to form $Ca(OH)_2$. This weathering takes time, needs a lot of storage space, and the result often has not been sufficient and leads to a high amount of fines, which cannot be used. Stockpiling time depends on the particular conditions and properties of the slag. Aging time is different from one site to another (Juckes & Thomas, 1989; Matyas, 1978; Piret, Lesgardeur, & Delmarcelle, 1980). For instance, steel slag is customarily stockpiled for 3–12 months in Russia; for 5–8 months in Germany, the United States, and some other European countries; for 6 months in Japan; and for 12 months in the United Kingdom. Although studies have found that steel slag reaches sufficient stability to be used in road construction after 6 months to 1 year of storage (Mahieux, Aubert, & Escadeillas, 2009), stockpiling and aging cannot ensure complete elimination of expansion. Sometimes, even if the steel slag is stockpiled for a couple of years, it still cannot be guaranteed that there will be no expansion. This suggests that it is important to test slag chemically and physically and understand the extent of potentially harmful constituents and resultant expansion. The disadvantages of stockpiling and aging are the land area and the extended period of aging normally required.

Accelerated aging by hydration and aeration of BOF slag was developed in Brazil and named ACERITA (da Silveira, e Silva, Agrizzi, de Lana, & de Mendonça, 2005). The aging time needed is approximately 2 months to reduce the volume expiation to within an accelerated level for paving, which is less than 3.0% of f-CaO.

5.4.2.3 Hot pouring

The hot pouring method was developed in the 1950s. Pits are located adjacent to, or in front of, the furnace (Barnes & Strong, 1980). The molten steel slag is poured into the pit to form several layers. After pouring, each layer is sprayed with water, prior to pouring subsequent layers, usually three, until the total thickness is approximately 30 cm

(12 in.). After cooling, steel slag is bulldozed and removed for crushing. The disadvantages of this method are poor working and environmental conditions during processing; extended equipment and capital investment required; quality control of treated steel slag, which is affected by uneven pouring of layers due to the variation of adhesiveness of semiliquid slag; and sometimes, explosions that occur when the subsequent layer of hot steel slag is poured because of too much spray water or accumulation of rain water.

5.4.2.4 Air chilling

In the air chilling method, molten steel slag pots containing slag are transported to the air chilling equipment, rotated to tip out the slag, the flow being controlled by a "mid pot," and high-pressure air from spray nozzles is blown to break up and granulate the slag (Sasaki, Niida, Otsuki, Tsuchiya, & Nagao, 1982). Recycling of heat can be carried out at the same time. The specific characteristics of this method are that the instability of the steel slag is improved, explosions are avoided, and heat from the molten slag can be recycled.

5.4.2.5 Water quenching

Due to the success of water chilling for granulated blast furnace slag, several experiments with steel slag have been made in several countries by using water quenching. The problem is that explosions cannot be avoided if related technical factors are not properly controlled (Relf, 1976).

5.4.2.6 Plate chilling

Since the 1970s, the trends in steel plants have been toward high output and large scale. Quick slag discharge and safety insurance in production are required. Oita steelworks in Japan developed the plate chilling method by combining the hot pouring and water chilling processes (Takashima, Nagashima, Hori, Kimura, & Takahashi, 1981). Three separate cooling stages are incorporated in this technology: cooling in plate, cooling in cart, and cooling in water pool before the product is transported, dried, crushed, magnetically separated, sieved, and stored ready for use. This technology has improved the stability of steel slag. This is a safer method, with less pollution involved; however, very high investment cost is necessary. This method still cannot ensure that steel slag is poured from the cart evenly and has not completely solved the instability, although it is improved greatly.

5.4.2.7 Instant slag chilling process

The instant slag chilling process is in operation at Nippon Steel's Oita and Yawata works. Originally, BOF slag was treated by the yard process. At Nippon steel, each steelworks employs the outdoor or indoor type yard process. However the yard process had problems, including (i) low capacity—a substantial increase in capacity within the limited space could not be expected; (ii) unfavorable working environment—slag was treated in an environment where large quantities of dust was generated and the temperature was high; and (iii) as high-temperature slag was handled, the slag handling equipment was subject to heavy wear and tear. Oita works started the development of a method of pouring molten slag into a steel box in the 1970s (Takashima et al., 1981). The instant chilling process consists essentially of four stages. The first stage is air-cooling, where the molten slag is located on shallow plates (boxes) to give a bed thickness of approximately 100 mm (4 in.) and air-cooled for 4 min. This is followed by an initial water cooling cycle during which the slag bed is continuously water sprayed for approximately 20 min to produce an end temperature of 500°C (932°F). After initial water cooling the slag is loaded into slag carts and transported to a spraying station for further water spraying for 4 min and an end temperature of 200°C (392°F). Finally, the slag is placed in a water pool and cooled to around 60°C (140°F) to complete the process, ready for magnetic screening. The slag is treated in a batch process with total treatment time of 1.5–2.5 h. This treatment process generally produces low pollution and particle size of 30–50 mm (1.2–2.0 in.) with low f-CaO content (2–4%). Because relatively thin slag layers are water sprayed in the shallow box, the risk of explosion due to generation and entrapment is avoided.

5.4.2.8 Self-powdering

Based on the principle that the dicalcium silicate will expand in volume due to the transformation from β-C_2S to γ-C_2S during slow cooling, materials containing silicate were added to enable the formation of a greater amount of β-C_2S (Gong & Tan, 1983). During cooling from the molten state, steel slag would powder naturally, thus processing the steel slag. Some trials were carried out in Russia using this method. However, this method neglects the free lime, the main detrimental component, the transformation does not continue at ambient temperature, and has little effect on the use of solidified steel slag.

5.4.2.9 Spent acid treatment

Steel slag was treated by spent acid, saturated with spent H_2SO_4 pickle liquor, and stored for at least 1 month, in the Levy Company, USA (Emery, 1977). This method was effective for limiting the expansion potential of steel slag for use in base construction.

5.4.2.10 Property modification

Property modification of steel slag was conducted after steel slag was discharged to improve the stability of steel slag. Tests in some countries have shown that adding blast furnace slag or fly ash to the steel slag improved the stability of steel slag. Some research programs resulted in patents that were reflected in Japanese Patents (JPs). These included the addition of materials containing silicate or aluminate into steel slag during discharge (JP 74-58107); putting fine steel slag into molten blast furnace slag (JP 76-61278); adding boric acid or borate into steel slag (JP 78-43690); and mixing molten BOS slag with special steel slag containing Cr_2O_3 to raise the content of Cr_2O_3 above 2% (JP 78-30997). The aim of all of these methods is to eliminate the unstable materials in steel slag.

5.4.2.11 Steam treating

Steam treatment of the steel slag, as carried out at Nanhui cement plant in Nanhui county, Shanghai municipality, China, effectively solved the expansion problem resulting from free lime and made steel slag blended cement stable (Wang, 1986; Wang & Lin, 1983). The powdering ratio, as defined previously in this chapter, of high basic steel slag ranges from 50% to 80%; after steam treatment, particles with diameter less than 80 μm constitute 30% of the total, imparting hydraulicity to the slag (Sun & Yuan, 1983).

5.4.2.12 Self-dissolving

In this method, hot steel slag is put into a sealed pressure tank, holding approximately 100 kg (220 lb) of steel slag (it can be a smaller or larger amount depending on the trial scale) (SRIM, 1982). Molten steel slag can produce large amounts of steam that can convert more than 80% of f-CaO to $Ca(OH)_2$. The powering ratio exceeds 80%. The steel slag treated by this method can be used as a construction and building material or as a mineral resource. The volume of the scaled tank for commercial use is sufficient to hold 5 tonnes of steel slag.

Recently, tank-type hot disintegrating, rotary cylinder technology processing is reported to produce small particle size, good steel slag separation, active promotion of slags, and be conducive to the comprehensive utilization of steel slag (Liao, Zhang, Ju, & Zhao, 2013).

5.4.2.13 Pressure treating

To develop an economical and rational aging process, Sumitomo Metal Industries, Ltd. (SMI) and Kawasaki Heavy Industries, Ltd. (KHI) worked together to complete and implement an actual aging plant (Morishita et al., 1997). Japanese Industrial Standards for aggregate are used as the standards of the final product. Slag expansion was measured according to those standards before shipment. According to those specifications, the slag should be evaluated by a method of immersion in 80°C (176°F) waster for 6 h a day for a duration of 10 days, and then its expansion should be measured (Table 5.4).

Table 5.4 **Comparison of aging time using different methods**

Method	Approximate aging time
Natural weathering	2 years
Hot water immersion	2 weeks
Open-yard steam injection	2 days
Newly utilized high-pressure steam	2 h

Data from Morishita, S., Kiode, H., & Komai, K. (1997). The development of the new aging process of steelmaking slag. *SEAISI Quarterly*, (January), 37–48.

It was confirmed that when the slag aged under saturated steam of 0.6 MPa (87 psi) absolute pressure, the aging could be completed in 2 h to attain the 0.5% expansion ratio of water immersion as targeted. The speed of this reaction is 24 times faster than that of conventional steam-yard aging. The 0.6 MPa saturated steam is readily available in SMI's Wakayama Works because the steam is recovered as waste heat from the iron- and steelmaking pyroprocess by a waste-heat boiler. The process includes an autoclave, a slag transportation wagon, a loading deck, a shunting deck, two slag baskets, and so on. The slag is fed into a basket. The filled basket is transported to the autoclave by a transporting wagon and then exposed under 0.6 MPa pressure of saturated steam. After aging is completed, the basket is taken from the autoclave and the slag is quenched by water spraying. Then the basket can be opened widely at its bottom and the inclination of the bottom wall is sufficiently steep for efficient discharge of slag.

5.4.2.14 Other methods

Rapid cooling: Steel slag samples were modified on a lab-scale basis in two ways for comparison with the original slag by Toaasvainen, Engström, and Yang (2005). First, remelting and water granulation (rapid cooling); and secondly, remelting and cooling in the crucible (semirapid cooling). It concluded that a rapid cooling rate has an influence on the formation and distribution of slag minerals and consequently enhances the volumetric stability of steel slag.

Borax addition to treat ladle slag: Ladle slag is obtained in the process of prodding stainless tool steel by using EAF and vacuum degassing technologies. The slag contains di- and tricalcium silicate and gehlenite in the CaO-Al_2O_3-SiO_2 system. After air-cooling the slag decomposes into dust, causing environmental problems. Slaking slag pollutes the surroundings of the dump site. Trials were conducted by adding borax into liquid ladle slag immediately after the ladle refining (Rozman, Lamut, Debelak, & Knap, 2007). The slag did not decompose as dust after the cooling. Stable slag contains sodium and boron oxide. The addition of borax into the slag after casting the steel was not efficient because borax reacts only liquid slag.

5.4.3 Mechanical handling

After liquid slag is discharged from the furnace it is dumped, cooled, and processed to recover the metallic in the slag. The air-cooled slag fraction is further crushed and screened to produce slag product. Many technologies are available to offer the ultimate solution for handling slag by simultaneously extracting the valuable metallic and destroying any hazardous components in an environmentally sustainable manner. Slag processors may handle a variety of materials, such as steel slag, ladle slag, used refractory, and pit slag, to recover steel metallic. Scrap removed from BOF and EAF slag is recycled back into furnaces (Topkaya, Sevinç, & Günaydin, 2004). Some steel slag is being recycled to blast furnace burden with the remainder being processed. All these materials on-site must be source separated, and well-defined handling practices must be in place to avoid contamination of the steel slag aggregate. The slag processor must also be aware of the requirements of the end user. Aggregate requirements, such as gradation, moisture content, and material handling practices to avoid segregation, must be satisfied before delivery of a quality aggregate to final use.

Slag is difficult to recycle back through the primary product plant facility because of environmental compliance issues and their physical form. The challenge is finding a viable solution that is capable of separating the valuable recyclable metals from slag. Scrap handling and preparation is to prepare scrap to the required size. Through the use of crane-mounted shears, attachments, and multiple burning technologies, each specific need can be met.

Direct furnace digging can be done with enhanced front-end specialty loaders. These specialty loaders are also used in digging the blast furnace pits at integrated locations. A slag handling crane is used to distribute slag under the conveyor line to the other areas in the slag; slag pot haulers are used to remove slag from melt shops.

Reclaimed scrap that is high in metallic content can be created through the use of scrap and slag separator plants to satisfy the requirements of each steel operation. The reclaimed metallic scrap is returned to the steelmaking and ironmaking facilities. The operations include loading and unloading scrap, organizing and operating scrap yards, and loading charging boxes and scrap buckets for direct charging.

5.5 Summary

Liquid slag from the steelmaking or other ferrous and nonferrous making furnaces is dumped, cooled, and processed to recover the metallic in the slag. The slag fraction is further crushed and screened to produce slag aggregate or other products. In the steel industry, slag processors may handle a variety of materials, such as steel slag, ladle slag, used refractory, and pit slag, to recover steel metallic. These materials must be source separated, and well-defined handling practices must be in place to avoid contamination of the product. The slag processor must also fully understand the requirements of end products. The technical requirements of slag product, aggregate for example, such as gradation, moisture content, and material handling practices to avoid segregation, must satisfied before delivery of a quality slag product to the end user.

Processing and treating are vital in the production of various slag products. Evaluation tools for various testing are important, as are the methods. It is essential to evaluate the effectiveness of processing and treating methods selected for a specific slag. Both test methodologies for slag itself and end products are equitably important in the establishment of usability criteria linking properties of slag and the end product.

Slag process technology has been innovated in the last half century and will continue in the future. It is reasonable to believe that slag will be fully used as a valuable resource in construction engineering and other applications. The key technology of the steel slag treatment process is to improve the volumetric stability of steel slag. Molten steel slag is alkaline, with lower temperature, the viscosity increases sharply, the liquidity varies and is one of the important factors affecting steel slag processing. Rational slag treatment technology should be selected according to the need, properties of slag, and final product requirements.

Ferrous slag processing is the focus of this chapter. However, for nonferrous and nonmetallurgical slags, air-cooling and granulating are the main treating methods used. Coper and zinc slag can be granulated. Bottom ash slag from a power plant can be water quenched. Special treating of nonferrous and nonmetallurgical slags will be discussed with their utilizations in each following corresponding chapter.

Questions

5.1 What causes the variability of the chemical composition of slag?
5.2 What are the major mineralogical differences of air-cooled iron blast furnace slag and granulated blast furnace slag?
5.3 What are the four types of iron blast furnace slag products?
5.4 Why is lowering f-CaO content the primary task in treating steel slag?
5.5 What pretreatment methods can change and lower f-CaO content? Give an example and explain.
5.6 Any other ferrous slag has volume expansion issues?

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Philosophy of utilization of slag in civil infrastructure construction

6

6.1 Introduction

Molten slag is coproduced with many metallurgical processes: iron- and steelmaking, for instance, and special processes, including coal-fired thermal power generation and municipal solid waste incineration. It is subsequently cooled by different methods, including air, water, pelletizing, foaming, or granulating, for use, or, unfortunately in too many cases, disposal. Ferrous (eg, iron and steel) and nonferrous (eg, copper and nickel) metals are the most commonly used structural and functional materials worldwide. Nonmetallurgical primary product production (eg, phosphorus) and coal-firing processes are essential production activities of modern society. The large quantities of slags resulted and their potential impact on the environment have prompted materials scientists and civil engineers to explore the technically sound, cost-effective, and environmentally acceptable use of a wide range of slags in civil infrastructure construction.

In the broad sense, the comprehensive utilization of slag will have significant benefits in three major ways. First, there will be a substantial reduction in environmental pollution due to changes in the traditional practice, whereby the existing material is disposed of by dumping or stockpiling. Second, the use of such material will supplement, or replace, the need for using natural materials, thereby resulting in protection in energy requirements associated with the winning of natural materials. Third, there exists the possibility of altering or modifying physical, chemical, and mechanical properties of conventional and end materials incorporating slag (with or without incorporating other nonconventional materials) to produce various engineering materials for specific applications. The comprehensive and rational utilization of slag should comprise these three aspects.

Slag is a broad family comprised of many different types of slags: ferrous, nonferrous, and nonmetallurgical. Fig. 6.1 categorizes most of the slags in the three major types. In this text, most slags from each group are discussed.

The comprehensive use of slag is becoming increasingly important in construction practices for energy, natural resources, and environmental conservation considerations. In the last couple of decades, researchers have conducted research on various slags' uses in construction, including use as aggregate in hot-mix asphalt (HMA) (Ahmedzade & Sengoz, 2009; Kavussi & Qazizadeh, 2014; Shen, Wu, & Du, 2009; Wu, Xue, Ye, & Chen, 2007; Xue, Wu, Hou, & Zha, 2006), use as granular materials (Akinwumi, 2014; Buzatu et al., 2014; Dayioglu, Aydilek, & Cetin, 2014; Dunster, 2002; Shen, Zhou, Ma, Hu, & Cai, 2009; Suer, Lindqvist, Arm, & Frogner-Kockum, 2009; Tasalloti, Indraratna, Chiaro, & Heitor, 2015), use as fine or coarse concrete aggregate

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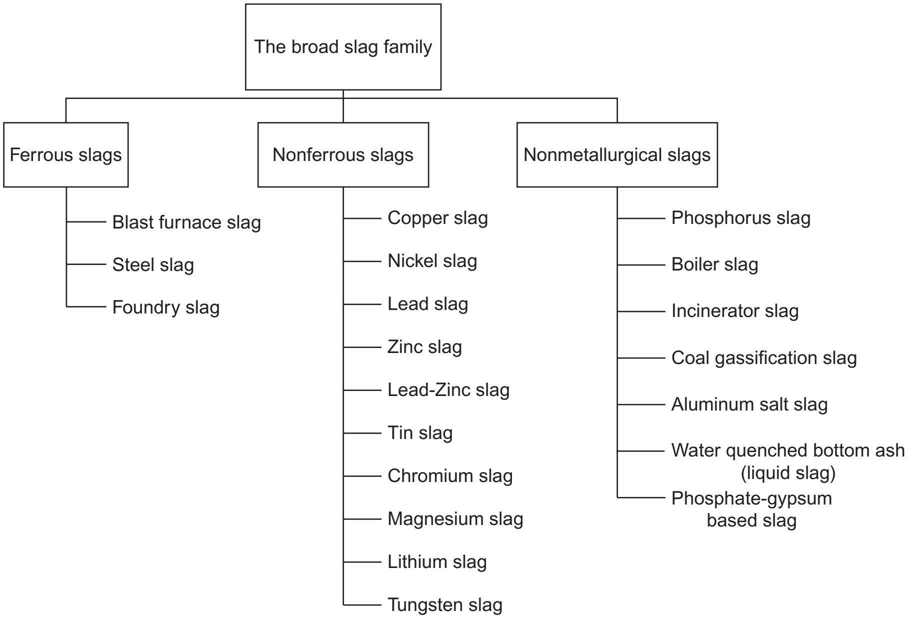

Fig. 6.1 The broad slag family and coarse classification.

(Alwaeli, 2013; Anastasiou & Papayianni, 2006; Beshr, Almusallam, & Maslehuddin, 2003; George & Sorrentino, 1982; JP, 1982; Kawamura, Torii, Hasaba, Nicho, & Oda, 1983; Li, Yao, & Wang, 2009; Manso, Polanco, Losañez, & González, 2006; Maslehuddin, Sharif, Shameem, Ibrahim, & Barry, 2003; Montgomery & Wang, 1991, 1992; Qasrawi, Shalabi, & Asi, 2009), and use in cement manufacturing (Conjeaud, George, & Sorrentino, 1981; Mahieux, Aubert, & Escadellas, 2009; Murphy, Meadowcroft, & Barr, 1997; Reddy, Pradhan, & Chandra, 2006; Sun & Yuan, 1983; Tsakiridis, Papadimitriou, Tsivilis, & Koroneos, 2008; Wang & Lin, 1983; Wang & Yan, 2010). However, it must be noted that some of the research is in laboratory experiment stages with or without field trial and demonstration except for blast furnace slag, which has been extensively used for several decades and growing steel slag-related applications. To date, it is not uncommon in some regions in the world to find that certain types of slag are still receiving little attention with regard to useful purpose, with the accepted tradition being to merely dump the materials as landfill. The potential use and overall process of the utilization of slag can be illustrated by Fig. 6.2.

The successful utilization of slag in construction generally depends on an overall process consisting of several stages from the slag production to end uses. As illustrated in Fig. 6.2, any of the stages can affect the properties of slag and the performance of the end products. These stages include pretreatment and posttreatment of slag, chemical and physical characterization, identification of the factors that affect slag properties, and the evaluation of performance for the intended use. Studies on the comprehensive utilization consist of three main stages: (i) selecting a treating and processing procedure, (ii) characterizing intrinsic properties, and (iii) evaluating

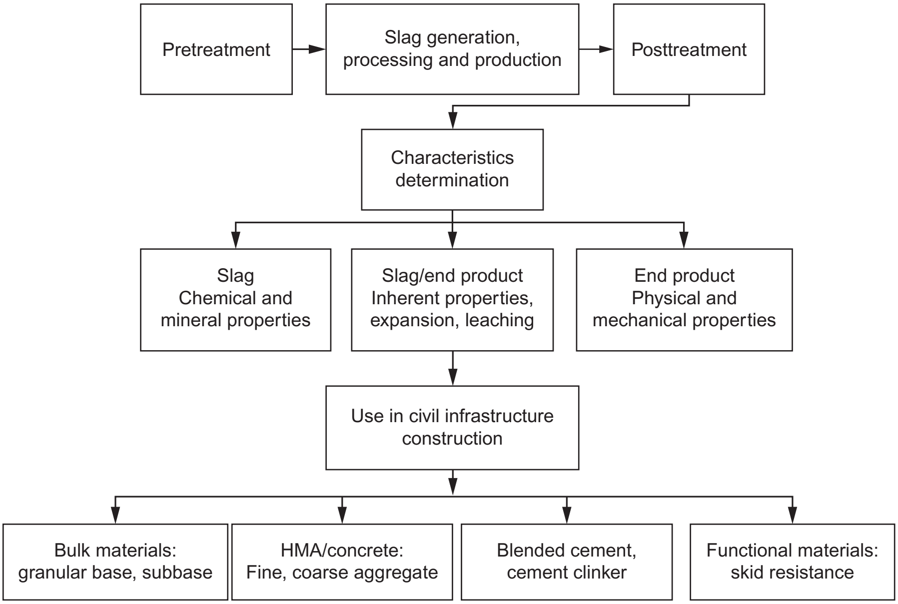

Fig. 6.2 Overall process of slag utilization in civil infrastructure construction.

performance properties of end products. As indicated in Fig. 6.2, the use of slags includes several broad applications, including use as bulk materials, asphalt or concrete aggregates, cementitious applications, and functional materials.

Laboratory testing, field trialing, and property and performance quantifying, with appropriate specifications and quality requirements, are the trilogy of research and development of slag utilization. The ultimate purpose of slag utilization research is to open avenues for the proper uses of each individual slag with specific characteristics. There are three main points fundamental to conducting the effective study of a specific slag, which forms the basis for uses in civil infrastructure construction.

First, there must be a sound understanding of the overall compositional and physical properties of the specific slag being investigated, especially any potentially adverse characteristics (volume expansivity related to hydratable oxides for steel slag, for instance). Typically the slag properties include compositional (as oxides and mineral composition), physical, and mechanical portions. All these properties need to be compared with those of the conventional material that may be replaced or used in conjunction with slag. The comparison study should include the properties of slag and conventional or traditional materials, which may be replaced by the specific slag, or used in conjunction with the slag. This use may incorporate other nontraditional material(s) to modify the prosperities of end product. Due to the inherent nature of variability in chemical composition, a successful use of one slag may not relate directly to another slag of the same type.

Second, to achieve appropriate and optimum utilization of slag, it is essential to have a comprehensive understanding of the production, properties, design methods, construction uses, and specifications of the conventional material that slag may replace or incorporate with. This is because the slag may replace the conventional material or may be used in conjunction with it. The conventional materials include aggregate (granular base, for instance) or cementitious (Portland cement, for instance). The relationship between slag and conventional materials in terms of their properties and performance must be understood and investigated experimentally and theoretically so that more quantified potential use of specific slag can be thoroughly exploited and reached.

Third, it must be recognized that slags are unique and are distinct and different from any natural mineral materials. Like any other by-product or coproduct (or waste, unfortunately too often), slag is a type of special raw material with its own characteristics that must receive additional processing for uses in construction. Each specific slag, in terms of type, process, and source, should be fully evaluated for each proposed use, given the significant differences in properties that can be involved and the specific performance requirements for bulk, aggregate, and cementitious uses. It is important, therefore, that civil construction material and construction specifications based on conventional mineral resources and materials, with special requirements for slag use, do not preclude the use of suitable quality slags with demonstrated satisfactory performance for the intended purpose. The importance of proper slag processing, with quality control, for approved construction uses, cannot be overemphasized. To promote the future research and exploration of various slag use, the philosophy of utilization of slag, quantified properties of slag and end products, and quantification work that leads to usability criteria are presented in this chapter.

6.2 The methodology of slag research and utilization

It is clear that specific requirements, quality control procedures, and specifications based on quantitative criteria are critical for the correct use of slag. As discussed in Chapter 5, processing, evaluation, and testing methods have been the topics of research on the properties of slag and how it can be rationally utilized. Because of the inherent difference between slag and any other natural mineral resource (eg, limestone or basalt) or any other artificial primary product (eg, Portland cement), the aim and methodology of utilization will be different. For example, steel slag may be interused with other materials to reduce the effect of expansion.

In addition to the specifications for conventional construction materials and construction, special technical specifications for special use of slag can be developed as a supplement to conventional uses. For instance, in some applications, the amount of slag used may be restricted within certain limits for the consideration of strength, stability, or unit weight, which suggests that the quantity requirements for slag use may be different from those for other natural and artificial materials, while the overall quality of final product meets or exceeds the requirements. In research, a comparison study of slag to other materials should be conducted to identify the similarities and differences and avoid any confusion of slag with other materials. For example, in the study of the expansion mechanism of steel slag, specific properties of steel slag and Portland cement may give rise to differing effects. Transformation of β-C_2S to γ-C_2S and existing $C_{12}A_7$ should be avoided in the production of Portland cement, because they will lower its hydraulicity. However, in steel slag, β-C_2S to γ-C_2S transformation and existing $C_{12}A_7$ are not generally the consequence of expansion, although they may still result in lower hydraulic activity.

6.2.1 The relationships between slag characteristics and end product performance

The comprehensive utilization of slag is a topic that requires a thorough knowledge of the materials involved. A sound understanding of the properties of both slag and the target uses (ie, the end products) is essential. That means that the intrinsic properties of slag have to be investigated and characterized for its potential use, while the requirements of the end products (construction materials and construction methods) should be well understood. Without the study of both aspects, utilization will be blind, inactive, or low grade. It is common that in its utilization, slag is a component of composite materials with other materials or incorporated in a matrix material.

There are three relationships that are considered important for slag utilization in construction as shown in Fig. 6.3: (i) the relationship between chemical and mineral composition and potentially adverse properties, (ii) the relationship between the adverse properties and the properties and performance requirements of the end product, and (iii) the rational use of the end product with different properties to ensure its optimum application. For example, volume expansion may be the main factor likely to affect the successful use of a steel slag as a construction material. Volume expansion is dependent on the chemical and mineral composition of the specific slag and thus it is critical to evaluate the expansion property of slag and the performance of the end product including expansion behavior.

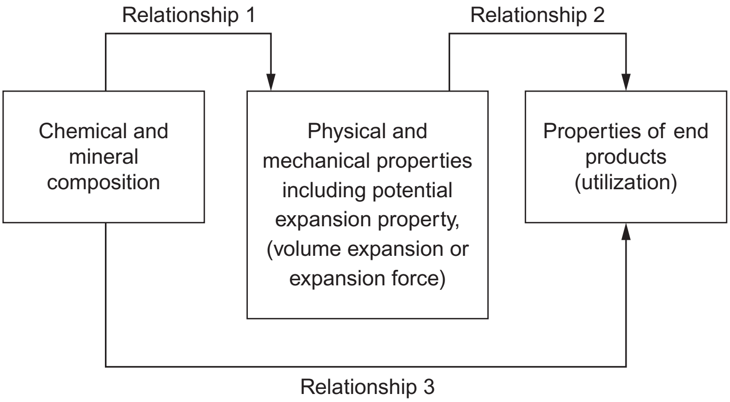

Fig. 6.3 Key relationships for slag utilization in construction.

To effectively use a slag, it is necessary to understand how its chemistry and mineral composition affect any potential negative properties and how the negative properties can affect the physical and mechanical properties of the end product. Based on this understanding, it is necessary to treat and modify the properties of slag and conduct proper quality control during the slag utilization process. The slag, after it is properly treated and modified, should be ready for use in construction. Once the physical and mechanical properties meet the performance requirements for the end product, the utilization process becomes practicable. Therefore, it is imperative that all potential negative properties and/or deleterious components of a specific slag be thoroughly checked and treated for the intended and optimal use.

Slag is energy-containing. When slag is rapidly solidified from the molten state to a vitrified form, latent energy might be locked in it. For this reason, in terms of determining the use of a specific slag, proper attention should be paid to the optimum use of its energy potential. This is one of the main objectives of slag utilization, along with protecting the environment and taking technical benefits for value-added uses. In this respect, the term "slag utilization" can be defined as the extensive and effective use of a slag to achieve a high extent of using its energy and mineral. Under this definition, landfill is clearly not utilization and does not contribute to a sustainable society.

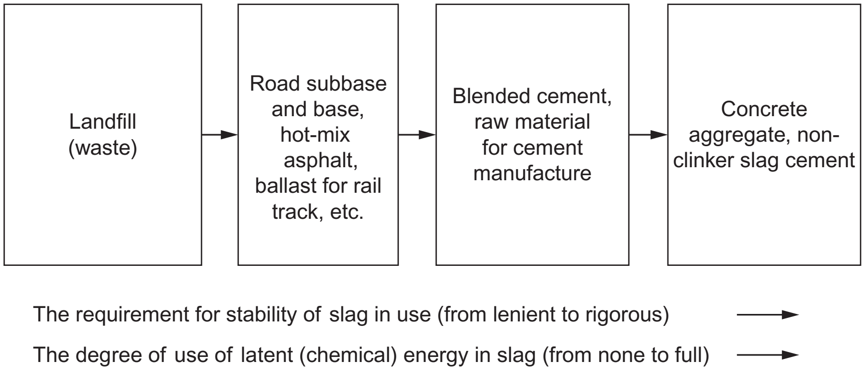

Fig. 6.4 Typical grades of slag utilization in construction.

From Fig. 6.4, it is essential to focus on increasing potential latent energy uses of slag where applicable. For instance, the use of slag as a cementitious material in blended cement can be considered to be energy recovery and value-added uses more than just bulk and inert aggregate uses (see Fig. 6.4). Therefore, more rigorous quantitative assessment is generally necessary for a higher degree of stability and end uses of a slag.

In using a slag in construction, hazardous components must be identified and processed before put into use to eliminate any risk of hazardous exposure, which can potentially affect the ecology of humans and other living things. For this reason, hazardous components must be removed or neutralized in the end products by the contractors certified to handle them. Environmental considerations in the use of slag are discussed in Chapter 7.

6.2.2 *Quantification of the properties of slag and end products*

Rational and useful criteria for utilizing a slag for an intended use should be established by the quantification work. In other words, each specific slag must be fully quantified and checked for each specific use according to rigorous quantitative assessment guidelines.

That slag is not fully utilized is mainly due to the lack of exhaustive quantification work to illustrate and quantify the performance properties of the end product, such as expansion potential for steel slag and strength properties. For example, how to measure the expansion of steel slag? What has been done, what hasn't? The technical opinions and laboratory testing results not supported by thorough characterization and performance testing should not be used to encourage the use of the slag in construction. Usability criteria can be determined from the quantification work; that is, the study of the basic properties of slag, measureable and quantified properties, and the required performance of the end products conforming to conventional requirements including stability and deleterious material control requirements.

Relevant quantification work on slag includes special tests and measurements; specification requirements; processing requirements; quality control procedures, laboratory testing, and field evaluation; and last but not least, relating the properties of slag to the end product performance. For this quantification work, technical suitability should be matched with environmental factors and cost-effectiveness. For slag used as bulk materials or aggregate, the quantification requirements should be focused on the importance of long-term stability and durability in a wide range of environments and structures; for slag used as cementitious materials, the grindability of slag is another key factor to be considered in addition to the pozzolanic and hydraulic properties.

Quantified usability criteria are imperative for utilizing various slags at a large scale. The criteria development for the utilization of slag is critical for the intended uses in construction. To properly utilize slag in construction and ensure that both slag and end products are technically sound and durable, the following steps have to be followed: (i) select the right criteria for a specific use, (ii) conduct relevant laboratory testing to quantify the given sample, (iii) determine the suitability based on relevant criteria, (iv) conduct field quality control, and (v) monitor long-term performance. These five steps are the same for the use of conventional material. In this chapter, it has only been possible to outline the guiding methodology for slag utilization. Detailed quantification work examples of steel slag will be discussed in Chapters 9, 12, and 13. The author believes that this methodology can be easily adapted to the utilization of other slags such as nickel and copper. As a result, the requirements for a full quantification of the slag and thorough evaluation criteria for the intended uses can be clearly indicated.

It will be seen in Chapter 9 that for quantifying the use of slag in nonrestrained conditions, the theoretical equation for estimating and predicting volume expansion of steel slag can be deduced based on both chemical reaction and physical changes of free lime in steel slag during the hydration process.

It will be seen in Chapter 12 that for slag use in restrained condition or rigid matrices, expansion force generated by coarse steel slag aggregate can be deduced to convert the measured expansion force to expansion force of unit volume slag and an individual slag particle, which then can be used in the development of usability criteria for use in restrained conditions.

In Chapter 13, criterion is established for steel slag use in blended cement manufacturing, based on the f-CaO content and limitations. The requirements for a full quantification of a specific slag and thorough evaluation for intended uses will guide the comprehensive utilization of slag, along with the sustainable development objective of taking advantage of the full range of potential uses, particularly invested energy and cementitious activity.

6.3 Blending use of slag with other by-product or nonconventional materials

The term blending use is used by the author to refer to the use of slag with one or more other by-products or nonstandard materials in an end product to modify and/or enhance the properties and performance of the end product. Sustainability requires researchers to proactively respond to growing environmental concerns and natural resource shortages. The construction industry consumes huge amounts of natural resources, and good-quality construction aggregate becomes exhausted (Collins, 1976; Lewis, 1982). It is imperative to develop a wide range of environmentally acceptable, technically sound, and economically viable uses for recycled materials and to transfer various "waste" streams, into useful material "resource" streams.

Blending the use of slag with other suitable recycled materials or by-products is an innovative way to fully utilize slag and any solid recycled materials. As shown in Fig. 6.3, the properties of the end products are related to the properties of the slag and other raw materials. By incorporating other recycled materials with slag, the properties of end products can be modified.

There are many byproducts or recycled materials available for use in construction; for example, slag, fly ash, silicon fume, scrap tire rubber (STR), recycled concrete aggregate (RCA), waste glass, phosphogypsum (PG), and recycled roofing shingle. Some of them have been successfully used in construction; some are undergone investigation. People normally and naturally focus on one of the materials in the beginning, if adverse characteristics are found, the development process may remain stagnant. This is probably one of the reasons why it normally takes longer time to develop the practicable utilization of a by-product than that of a conventional material.

Inhibiting factors exist for users and the public in slag and other recycled materials utilization. These factors may come from the following:

- Inherent variability
- Liability concerns for innovative technology
- Inappropriate environmental constraints
- User conservatism
- Obsolete specifications
- Lack of technical guidance

Of these factors, only the last one is technically related (ie, lack of technical guidance). Any "restrictions that prohibit the use of 'recycled' materials without technical basis should be removed" (Sullivan, 2014). The questions facing researchers are what is the technical basis? How to develop the technical basis? Quantifying the properties, developing usability criteria, and developing the optimum proportions of multiple recycled materials can answer these questions and can enhance the properties of the end product.

6.3.1 The ultimate goal of blending use on nonconventional

The probabilities and ultimate goals of the blending use can be asked by these questions: People might say the following "equations" are ridiculous:

$$1+1>2(?);\quad 1+1=1(?);\quad 1+1=0(?)$$

Yes, if they are in mathematics. However, it will be possible if the property of an end product is considered as the sum, people would agree with the following relations:

$$\text{Advantage} + \text{Advantage} > 2\,\text{Advantages}$$
$$\text{Advantage} + \text{Disadvantage} = 1\,\text{Advantage}$$
$$\text{Disadvantage} + \text{Disadvantage} = 0\,\text{Disadvantage}$$

Because the inherent properties of various materials vary, the right combination of them can crate better composite end materials than by using a single one. Therefore the ultimate goal of blending use is to minimize the disadvantages of individual recycled materials and maximize the advantages of the by-product and end products produced. From a slag utilization point of view, we need to "marry" slag with other by-products to maximize the technical and economic benefits.

For example, steel slag possesses excellent mechanical properties. Its Los Angeles abrasion value is in the range of 5–31 and its polish stone value is in the range of 50–63. However, its specific gravity can be as high as 2.38–2.76 and its unit weight as low as 1153–1442 kg/m^3 (72–90 lb cf). And steel slag may contain free lime and periclase that may cause volume instability, and aging and treating are needed. High specific gravity has limited the use of slag in areas far from the source site.

However, the specific gravity of processed STR is much lower, in the range of 1.02–1.20, with higher void ratio. Without blending use with other materials, STR provides limited strength or bearing capacity.

Considering use of slag and STR simultaneously, by adding 5–10% of scrap rubber, the specific gravity can be lowered to natural aggregate in approximately 2.5; by selecting optimum sizes, the void ratio of the blended material can be increased. The elastic nature of rubber would allow certain expanded volume in steel slag to be absorbed if used as unbound applications.

6.3.2 Potential recycled materials and by-products that can be co-used with slag

SR, PG, and RCA are discussed here as examples of many to illustrate the blending use.

6.3.2.1 Scrap tire rubber

Over 300 million scrap tires are generated each year in the United States. In Europe and some US states whole tires were banned from landfills. Waste tires have been environmental and financial issues. Not only do these tires occupy land and landfill spaces, they also pose health and safety hazards to the public. In many states, whole tires were banned from landfills. Ground tire rubber (GTR) use in road paving is successful, for instance, the utilization rate is very low. In a recent report (NAPA, IS #138), over 30 states have increased the use of processed scrap tire in infrastructure construction. To control the problems created by waste tires, governments have spent a large amount of money to remove, transport, store, and dispose the scrap tires. Scrap tires contain rubber, fiber, steel, and other materials potentially very useful in various applications. Therefore, a better approach dealing with waste

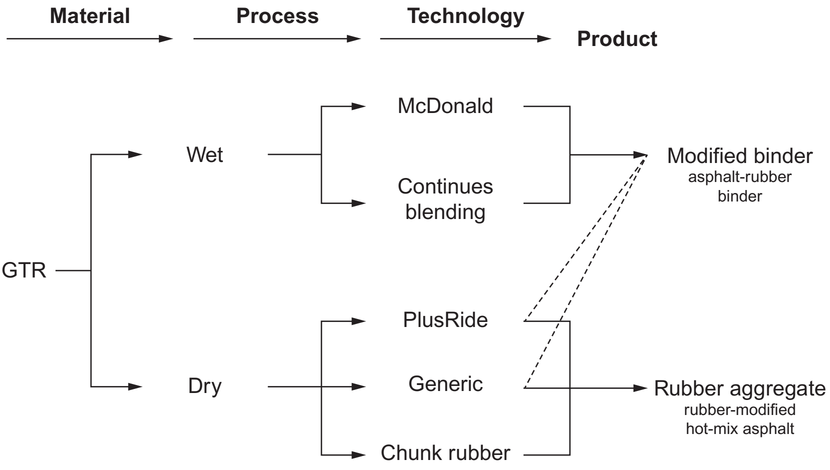

Fig. 6.5 GTR use in HMA.

Fig. 6.6 Processed scrap rubber.

tires will find innovative and profitable uses and motivate business to collect and process them for their own self-interest and create multiple win–win situations. Fig. 6.5 presents the process and use of GTR in HMA. It is noted that dry method may lower the stability of HMA and reduce rutting resistance. Fig. 6.6 presents processed STR in Cameron, North Carolina. With blending the use of slag and processed STR, HMA rutting will be lower than those without slag, or pure natural aggregates (Fig. 6.7).

Fig. 6.7 Rutting depth of the HMA prism specimens with and without slag.

6.3.2.2 Phosphogypsum

As discussed in Chapter 4, PG is a by-product from processing phosphate rock to produce fertilizers and other chemicals. The phosphate rock processing industry ranks fifth in the mining industry in the United States. In making fertilizer, phosphoric acid is produced from phosphate. To procure 1 tonne of phosphoric acid, approximately 4–5 tonnes of by-product, PG, is also generated. In 2013, 32 million tonnes of phosphate rock was processed in the United States; approximately 22 million tonnes of PG was produced in that year. Fig. 4.1 presents the phosphate rock processing and products. PG to date has not received enough attention with regard to utilization in the United States. Currently, a high proportion of the PG is either dumped or stacked. The decision to dump is partly affected by the relative leniency of environmental laws where PG is seen as essentially safe, but of no value; the decision to stack is partly affected, notably in the United States, by regulations that describe PG as low in radioactivity and hence subject to use only under permit. PG was reportedly used as synthetic construction aggregate in the United States and some European countries in the production of gypsum board, and for highway pavement, foundation, and embankment materials. The low utilization rate is due to lack of usability criteria and guidelines.

There is growing consensus that it is imperative to explore the rational applications of PG, and finding the right application for PG is pivotal to the turning point. The best way is blending use with other material such as slag.

The reason for PG not currently being fully utilized is often due to a general lack of quantification work on the properties of PG and the performance requirements of the end products (uses). Unfortunately, the impact of past utilization mistakes is very difficult to overcome even for proven uses. The blending use of slag and PG will possibly open new avenue for the use of PG in rational applications in construction, Fig. 6.8 shows stockpiled PG approximately 120 ft high.

6.3.2.3 Recycled concrete aggregate

Two of the problems facing many fast-growing areas are the decline of available disposal sites for demolition debris and the lack of good-quality aggregate resources

Fig. 6.8 PG stockpile.

for civil infrastructure construction. Both research and construction practice have proven that processed RCA from demolished concrete structures can meet or exceed the technical requirements for aggregates for use in aggregate base course, Portland cement concrete, and HMA. In the United States, 11 states have formulated specifications or guidelines to allow RCA use in new concrete. Other state transportation agencies have conducted research and trial projects on using RCA in concrete including Portland cement concrete pavement. However, RCA has a number of unique characteristics including lower specific gravity, which decreases with an increasing amount of reclaimed mortar and higher absorption, which increases with increasing the amount of reclaimed mortar; increased abrasion loss, which increases with

Fig. 6.9 RCA that can be used as an aggregate of non-structural concrete.

an increasing amount of reclaimed mortar; and ultimately, the concrete strength decreases with an increase in the amount of RCA incorporated in concrete. To improve the strength loss, research has been conducted on using slag aggregate to blend with RCA to maintain concrete strength; therefore saving cement use in concrete. Fig. 6.9 is RCA.

6.4 Summary

Intrinsic relationships exist between slag and end product that need to be explored and established. It is necessary to establish a quantitative relationship between slag and individual end products. For slag use in nonrestrained, restrained conditions or rigid matrixes, and the use in cement manufacturing the control parameters should be different.

Laboratory testing, field trialing, and property and performance quantifying are essential in utilization development. It is imperative to establish quantified properties and criteria to guide the utilization and clear the inhibiting factors contributing to low utilization rate. In view of energy, natural resources, and environment conservation, latent energy value invested in slag should receive a higher priority of attention and be fully utilized. It is essential to inclusively understand the compositional and physical properties of slag, the conventional materials, end products, and final uses in which slag is involved.

Questions

6.1 How does slag affect the performance of end products? Use one example to explain.
6.2 What categories can utilization of slag can be classified into?
6.3 Why blending use of recycled materials or by-products can modify the end products' properties?
6.4 What is the benefit of blending use of slag and PG?
6.5 What is the benefit of bending use of slag and GTR?
6.6 What is the benefit of blending use of slag and RCA?

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Environmental aspects of slag utilization

7

7.1 Introduction

The endeavor to utilize slag in construction is an important part of using by-products or nontraditional materials to realize the sustainability principles in natural resources, the environment, and the economy. In the last couple of decades, the steel industry and other base metal manufacturers have adopted the reduce, reuse, and recycle (3Rs) philosophy and efficient waste management in the production process. For example, the steel industry has taken up innovative measures and continues to make further efforts toward full utilization of the "wastes" generated to improve the environment. Due to the increasing natural drive to be natural resource conservative and cost-effective, there is a growing trend of adopting waste recovery technologies that reduce and reuse "waste" internally in the plant and consider the conversion of waste to by-products. Slag is a good example of the "wastes" generated in the steel industry, which has been developed into usable products in many applications. Other "wastes" in the steel industry include dust, sludge, refractory waste, cast house runner jams, and hot metal ladle skull. The use of these recycled materials prevents landfill waste, reduces CO_2 emissions, and helps preserve natural resources.

The time of using "waste" for slag has passed because of the continuously improved slag processing technology that converts slag into versatile products and the increased utilization rate of slags. However, when exploring a possible use of a specific slag in construction, one has to begin by reviewing policies and regulations set forth by government agencies for solid wastes to assess the feasibility of the application. Clear policies and regulations will help this assessment, overcome concerns over the utilization attempt, and help convert inhibiting factors, if they exist, to supporting factors in utilization.

To reduce barriers to the use of recycled materials, including ferrous and nonferrous slags, in construction, the US Congress has stipulated research into recycled materials to improve the durability of the surface transportation infrastructure. A number of states and local governments have passed legislation to promote using recycled materials in road construction. The industry has been continuously developing innovations in materials processing and new applications. Some states have introduced beneficial use determination to evaluate uses; however, there is no uniformity among states. State departments of transportation (DOTs) and state environmental protection agencies (EPAs) are trying to balance the desire for the use of recycled materials with concerns about potential environmental impacts. Interest is increasing within all levels of government to learn about advances in the use of recycled materials and by-products in transportation infrastructure construction and how they relate to sustainability initiatives within the transportation sector (FHWA, 2000).

In Europe, most countries have policies and regulations on the use industrial by-products in construction. Notably their policies and regulations generally promote

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sustainability, benefit from a pervasive public culture keen on using secondary materials, and occur within a social democracy that has promoted national behavior change. Many of the governments use an effective stakeholder consensus process to develop environmental specifications governing secondary materials utilization, including various slags. There are a wide variety of factors that influence the success of using recycled materials in construction—from national values to practical considerations at the regional level. Other drivers include a lack of virgin natural material, public opposition to aggregate mining, high hauling costs, opposition to landfilling, and high population densities. Many countries have formal policies and regulations for sustainable development in highway construction that embrace the use of recycled materials.

Culture building in the society is important. Policies and regulations should encourage minimizing the use of natural materials and promote the use of recycled and industrial by-product materials. Governments should cooperate with the industry by sharing risk and profit and providing unambiguous technical and environmental guidance and standards. High utilization rates of various slags can be reached if the culture and consensus are established among government, industry, and the general public.

7.2 Regulations and environmental evaluation

Strong environmental protection rules and regulations can derive different approaches in the determination of what type of slags, and where and how they can be used as a good engineering and environmentally friendly construction material. Any success using slag in construction is related to advances in all aspects of the sustainability model: a robust market, clear policy and regulation, economics, appropriate technical and environmental standards, and innovative technical processes.

Field-oriented and performance-based regulations need to be established and improved to guide the right use of slag in construction. Slag products should be evaluated on their technical merits for their highest possible use and not because of direct governmental mandates.

There is a lot of room to improve deficiencies that exist at the technical level. Regulations and test methods should be field environmental performance related. Many engineering test methods used for traditional materials do not necessarily predict the true nature of slag products or field performance of end products containing slag. Selection priority should be given to performance-related or performance-based test methods.

7.2.1 The necessity for performance-based regulations and guidance

The United States, Canada, and many European countries have enacted environmental protection and natural resource conservation laws and regulations since the 1970s and now different approaches, standards, and specifications have been developed in these countries. A brief review will reveal the varieties that are worthy of note.

7.2.1.1 Environmental law enactment in the United States

In 1970, the US National Environmental Policy Act (NEPA) was enacted, which requires that environmental impact be assessed and alternatives be considered whenever a federal action will have an environmental impact.

In 1976, the Resource Conservation and Recovery Act (RCRA) became a law that is the principal statute regulating hazardous and nonhazardous wastes. The RCRA was amended by the Solid Waste Disposal Act of 1980 and the Hazardous and Solid Waste Amendments (HSWA) in 1984.

Subtitle C of RCRA regulates hazardous wastes and contains provisions for characterizing, testing, treating, storing, and disposing of these materials. The RCRA requires that these wastes be manifested from "cradle to grave" (ie, from first generation until ultimate disposal). The RCRA offers a good example of the types of reporting and record-keeping requirements mandated in federal environmental laws. The RCRA also requires the EPA to establish a comprehensive regulatory program to control hazardous waste. The responsibilities for administering the RCRA are passed from the EPA to state agencies as these agencies show they have the authority and expertise to regulate hazardous waste effectively.

Subtitle D of RCRA deals with nonhazardous waste and requires states to develop comprehensive solid waste management plans. Once approved, the US EPA delegates the implementation and enforcement of the plans to each state. The federal regulations provide minimum standards for the treatment and disposal of nonhazardous waste. Many states have enacted more stringent standards and regulations.

In 1989, the US EPA published the *Solid Waste Dilemma: An Agenda for Action*. This document promotes a preferred hierarchy for municipal solid waste (MSW) management: source reduction, recycling, waste combustion (with energy recovery), and landfilling.

In 1990, the US Congress enacted the Pollution Prevention Act to encourage waste minimization through input substitution, product reformulation, industrial process redesign, and similar actions to reduce the quantity and toxicity of waste (FHWA, 2000).

In 1998, the FHWA published a document entitled *User Guidelines for Waste and By-Product Material in Pavement Construction* (Chesner, Collins, & MacKay, 1998), which lists 19 recycled materials and 6 major application categories for a total of 55 potential applications for using the materials. The document includes information about blast furnaces, steel, lead, zinc, copper, phosphorus, and boiler slags.

7.2.1.2 Experience in Europe

In many countries in Europe, similar environmental protection laws were promulgated during a similar time line, and have been amended in clearer and more detailed formats. Recycling at the national level is normally accomplished by environmental ministries that develop laws and compliance structure. National environmental research laboratories are responsible for developing test methods and approaches to evaluate environmental performance of solid wastes of different types and assisting in the development of standards and specifications. Implementation and regulation are occurring at the regional and local level. For example, the first solid waste utilization requirements became a law in 1983 (Statutory Order No. 568 December 6, 1983) in Denmark. Both this statutory order and the Environmental Protection Act, Disposal and Discharge Permit section, regulate small-, moderate-, and large-scale applications of incinerator ash and slag in road construction. Additional guidelines for road subbase were developed in 1989 by the Danish Highway Department dealing with the use of by-products including slags (Chandler et al., 1997).

The German federal states passed legislation in 1994 regarding incinerator ash management through Länder Working Group on Waste (LAGA), a working group established to assist in the development of detailed regulations aimed at implementing the waste management guidelines laid down by the federal government (NREL, 1995). The German legislation is intended to promote the reuse of as many residue streams as possible. Industrial by-products, MSW incineration, bottom ash and slag, are also used extensively in Denmark, The Netherlands, and France.

In the United Kingdom, The Netherlands, Denmark, Germany, France, and Sweden, government policies and specific sustainability initiatives support recycle and reuse in road construction. The consensus of stakeholders and each country's cultural attitudes toward recycling are extremely important. Swedish codes require that contractors document why they are not using recycled materials (FHWA, 2000). For some materials, several European countries are not concerned about the concentrations of constituents in a material, but rather the total amount that the end product will emit over the lifetime of its use. For example, the Dutch approach permits a small increase in the environmental burden to soil and water over a 100-year time frame. There are also differences in the approaches to evaluate the environmental behavior of materials. Many European countries use several leaching tests and other factors to evaluate potential utilization options and management requirements for the use of secondary materials, while the United States generally relies on a single regulatory leaching test.

The use of recycled materials is specifically emphasized in many countries' national environmental policies. These policies are supported by clear implementation guidelines. Test methods for evaluating environmental characteristics vary among countries, but there is agreement that field testing is critical to verify laboratory results and to determine the validity of using laboratory tests to predict performance in the field. The European Union (EU) 4th Framework Program Alternative Materials (ALT-MAT) project emphasizes this approach. The environmental ministries or national environmental agencies in each country generally develop the policies and regulations. These policies are implemented at the regional and local levels, often creating variability in their application among local and regional jurisdictions. National governments support research at national environmental laboratories to develop test methods, define approaches for evaluating environmental performance (including risk assessments), and assist in developing standards, specifications, and guidelines for using recycled materials in construction.

Approvals and permitting for using recycled materials in roads are normally done at the local level. In some cases this process can be very time consuming, adversely affecting the implementation of projects. In some countries (Denmark and Germany, for instance), there are broad categorical approvals for using selected materials in specific applications. More frequently case-by-case approvals are used for specific materials on the basis of conditions at a specific utilization site. The EU is attempting to develop a standard approach to evaluate environmental performance of recycled products, including those used in road construction projects.

In Sweden, environmental assessments for projects are completed and permits are approved on a site-specific basis using risk classification guidelines established for soils. These values were developed by considering the mobility or immobilization of constituents, dilution in pore water, surface water, ground water, means of exposure, and toxicological effects on humans and the environment. Sweden established the levels deemed acceptable for soils. An approach to evaluate the risk associated with using recycled materials proposed in Sweden are based on (i) surveying principles used to evaluate the risks of using civil engineering materials, (ii) reviewing international leaching protocols, and (iii) reviewing related procedures used in Sweden. The approach provides structure and guidance for establishing criteria needed for the assessment. It includes formulation of the risk assessment problem and exposure assessment, risk evaluation, and completion of the risk assessment. This approach results in the listing of substances, identification and establishment of guidelines for the specific use scenario, and establishment of technical and administrative measures required for the project. Also important is the establishment of procedures for quality control and quality assurance.

Some European countries participated in comprehensive research as part of the EU ALT-MAT program in an effort to increase the use of recycled materials in construction. Objectives of this research included defining the properties (environmental and engineering) of materials, establishing the relationship between laboratory testing and field behavior, developing an improved approach for assessing the risks of using recycled materials, and developing protocols for leach testing to evaluate environmental behavior of recycled materials when placed in the field. A key objective is to develop tests for characterizing materials and field performance (FHWA, 2000).

7.2.1.3 The necessity for performance-related regulations

Generally, clear and unambiguous government regulations with detailed engineering and environmental performance standards and test methods help to reduce uncertainties on the utilization of slag, allow slag to compete with natural materials, and convert inhibiting factors to supporting factors in the effort of utilization.

Laboratory work should be moved to performance modeling based on field validation. Leaching tests should be carefully selected for specific applications, road base, and embankments, for instance, in the environmental approval process. For example, the Dutch use this approach to determine adverse environmental impacts to background soils and ground waters, and permit a small incremental impact over a 100-year period.

Determining compliance with performance-based standards is not easy because the actual monitoring and testing of groundwater, surface water, and land and air quality are costly, complex undertakings. However, it is the right route that leads to comprehensive utilization of slag.

The US EPA guidelines spell out the operational and performance requirements to mitigate or eliminate the impact from solid waste disposal. Under operational standards, technologies, designs, or operating methods are specified to a degree that theoretically ensures the protection of public health and the environment. Some statutory laws were developed rather rapidly. The effectiveness of these statutes is somewhat in doubt. How will the EPA implement the RCRA in all cases? If states are given the responsibility to control hazardous and nonhazardous waste within their boundaries, how will they respond? (Weiner & Matthews, 2003). Performance-related regulations and standards should be established to provide clear guidance in the use of slag.

7.2.1.4 Life-cycle assessment consideration in slag applications

Life-cycle assessment (LCA) has emerged as an essential method to quantify the environmental benefits and drawbacks of solid waste management options (McDougall, White, Franke, & Hindle, 2001). LCA is defined as "the examination, identification, and evaluation of the relevant environmental implications of a material, process, product or system across its lifespan from creation to waste, or preferably to recreation in the same or another useful form" (Craedel, 1998). Although the proposed system boundary includes the waste from the moment of its disposal until conversion to an emission or a reusable material (ISO, 2006a, 2006b), various system boundaries of LCA studies have been used (Vergara & Tchobanoglous, 2012). A consensus should be formed to support regulations amendment for slag utilization by long-term cumulative concentrations and performance as the criterion of evaluation. LCA should be included in the entire service life of any specific application of slag, the end product and the actual field performance.

7.2.2 Environmental evaluation by leaching test

It has been proven that a wide variety of processed slags have no adverse impact to the environment and human health when used in construction, such as unbound granular materials, aggregate of hot-mix asphalt (HMA), concrete, and blended cement manufacturing. However, there are some concerns over some slags containing various levels of heavy metal or hazardous elements. A leaching test is normally used to simulate leachate movement of the unwanted materials in the field.

7.2.2.1 Leaching process and mechanism

Leaching is the extraction of a soluble material from an insoluble solid by dissolution in a suitable solvent. The process of leaching encompasses the physical and chemical reactions that carry the contaminant away from the matrix in which slag is used as a substituting material. The solvent or fluid that initiates the leaching process is called "leachant," and the resulting fluid containing the soluble material is named "leachate." The process of leaching is driven by concentration gradients that occur between the solid and aqueous phases. Theoretically, the molecular movement of chemical species will continue down the concentration gradient until equilibrium conditions are established (Conner, 1990).

There are two principal leaching transport processes: *advection* and *diffusion*. *Advective* transport occurs by the physical movement of the aqueous phase through or around the solid matrix. The leachant moves under the force of a hydraulic gradient and carries leached species away from the solid matrix. Advection is the dominant transport process in permeable systems with high flow rates. *Diffusive* transport occurs at a molecular level by the random motion of individual molecules or ions down a concentration gradient, moving the leached species away from the solid matrix. Diffusion continues until equilibrium conditions are established and thus the concentration of chemical species is uniform throughout the aqueous phase. Diffusion is generally considered to be a much slower transport mechanism than advection (Conner, 1990).

On initial contact with a leachant, rapid leaching of the surface of the solid matrix may occur via wash-off and dissolution processes. These processes continue until a leached layer is formed and thereafter the rate of leaching becomes limited by diffusion processes. Surface effects will theoretically be more significant in the leaching of fine-graded materials than in coarse-graded materials due to their higher surface area to volume ratio (Hill, 2002). Surface leaching processes will be affected by other physical properties of the material, as connected porosity and permeability influence the depth of the leached layer. Diffusion processes can occur within the solid phase, the aqueous phase, or across the solid-aqueous phase interface. Once a leached layer has been established in the solid matrix, the availability of further leachable species will be limited by the rate of solid phase diffusion, which is very slow. These physical processes produce an initial period of rapid leaching of chemical species that declines over time and becomes controlled by the rate of diffusion.

Leaching mechanisms are the factors that control the quantity of a chemical species leached from a solid matrix (mg/kg), the concentration of that chemical species in the leachate (mg/L), and the rate at which leaching occurs. The mechanisms can be divided into solubility, availability, and release controlled leaching.

Solubility controlled

Solubility is the maximum quantity of one phase dissolved by another under specified conditions. In leaching, the solubility of a chemical species will control the maximum concentration (mg/L) in the leachate. Under solubility controlled conditions, the leached quantity (mg/kg) is proportional to the ratio of the volume of leachant to the mass of solid matrix; that is, liquid-to-solid ratio (L/S).

The solubility of different chemical species varies considerably and the local leaching conditions can cause changes in solubility over many orders of magnitude. The most common factor affecting solubility is the pH of the leaching environment. The pH of a leachant has a significant influence over the solubility of most metals and some other chemical species. Many metals (eg, lead and zinc) exhibit a marked increase in solubility at both low and high pH values, or show no dependence on pH, such as sodium and chloride (van der Sloot, Heasman, & Quevauviller, 1997). The initial pH of a leachant may differ widely from the pH of the resulting leachate or in situ pore water, with a concurrent change in solubility. This pH modification may be particularly apparent in systems where L/S is low and the solid phase dominates the system. At high L/S ratios the initial pH of the solution may become more important.

According to van der Sloot et al. (1997) the pH in leaching systems such as road construction is usually governed by the dissolution of the major mineral phases from the solid or by uptake of atmospheric or biologically generated carbon dioxide.

Availability controlled

The maximum availability of an individual chemical species can be defined as the quantity (mg/kg) that will leach from a given solid matrix under the most intense leaching conditions. Once the available proportion of the chemical species has been leached, no further release will occur. Availability-controlled leaching is most likely to occur in systems with a high L/S ratio, where solubility limits are not reached. For availability-controlled leaching the total leached quantity (mg/kg) reaches a maximum and the higher the L/S ration the lower the resulting concentration (mg/L) of chemical species in solution. The degree of availability varies considerably for different chemical species and solid matrices. Availability-controlled leaching is most likely to occur for those chemical species that either have high solubility and mobility and thus leach rapidly, or alternatively have low mobility and thus leach only a small fraction of the total quantity. Availability for leaching is largely dictated by the chemical speciation in the solid matrix and its distribution between the solid phases of the material (Hill, 2002).

Release controlled

Release-controlled leaching is limited by the rate at which the chemical species can be leached from the solid matrix. In general, the rate of leaching is initially rapid and reduces with increasing time. Leaching may be rate-limited by solid-state diffusion or by species transfer across the solid-aqueous phase boundary. Mobility varies significantly between different chemical species and between materials. It is dependent on the properties of the solid matrix, such as porosity, permeability, and tortuosity, and the leaching environment, such as pH, complexation, redox, and temperature.

The governing mechanisms of leaching may switch between solubility, availability, and release-controlled depending on the properties of the solid matrix and the specific local environmental conditions. For example a shift in pH may change the solubility from low to high and therefore switch leaching from being solubility-controlled to being availability- or release-controlled. It is therefore important to understand the environment of usage of a particular material when assessing the suitability of that material for use.

7.2.2.2 Leaching assessment and test methods

Leaching is generally assessed using some form of laboratory leaching test. Leaching tests involve contacting a leachate with a sample of the solid material to produce a leachate that is then analyzed to determine its chemical composition. Many test methods have been developed to test various materials for a wide range of utilization and disposal applications. Most tests can be classified as either batch or flow-through (column) and are a variation of the same basic principles with slight modifications in the specific test conditions. The most common variables in leaching test are (i) sample pretreatment/preparation (particle size, drying); (ii) sample size (by mass or volume); (iii) leachate composition (distilled and/or deionized water, synthetic leachate, or rainwater, acidic solution); (iv) leachate pH (specified or material-controlled); (v) hydraulic conditions (batch or flow-through); (vi) mode and method of waste-leachate contact (agitated leaching vessel, agitated leachate, or nonagitated, upflow, downflow, under pressure); (vii) L/S (by mass or volume); (viii) duration (batch time, flow rate, overall duration); (ix) temperature (room, elevated, natural); (x) separation of leachate from the solid phase filtration, centrifuge (van der Sloot et al., 1997; WTC, 1990).

Batch tests are usually low cost, easy to operate, carried out over relatively short periods of time (hours to days) and experimental conditions (eg, pH) are relatively easy to control. However, batch tests sometimes are associated with arbitrary and high L/S ratios. Often such high L/S ratios will not exist under field conditions. Column tests on the other hand may be closer to field conditions and the material under testing will largely dictate experimental conditions such as pH. Column tests can be time consuming (tests over days and months), relatively costly, and be associated with problems such as channeling of materials along column walls and clogging. Below are a few leachate tests that are currently used (Scullion, Harris, & Rose-Harvey, 2010). Available standard leaching test methods are included in the following sections.

ASTM D3987 standard practice for shake extraction of solid waste with water

This is an agitated extraction test that is used to determine the mobility of inorganic constituents from waste material. A representative sample and reagent water with a 20:1 L/S ratio is shaken on a rotary agitator for 18 ± 0.25 h at 30 rpm, to rapidly produce leachate. The aqueous phase is subsequently separated and analyzed using the appropriate procedure and instrumentation. The intent is to produce leachate that is an estimate and not a representative of that which would be formed under field or site-specific conditions. The conditions used in the test (eg, agitation rate, L/S ratio) may not be suitable for extracting constituents from all forms of waste materials. As a result it is explicitly stated that this method should not be the sole determining factor for engineering design (ASTM, 2012).

ASTM D4874 standard test method for leaching solid waste in a column apparatus

This method uses a column apparatus in which reagent water is continuously passed through a representative sample of the waste material in a saturated upflow mode. The intent is that semivolatiles and volatiles and the maximum amount of metal species will leach from the solid. The method was written in a manner such that the user can adjust the specific operating conditions to meet particular objectives. The results obtained from this method will depend on the characteristics of the solid waste being tested and the specific operating conditions. As a result the method explicitly states that it cannot be used as the only basis for engineering design of a disposal site (ASTM, 2014).

Texas 7-day distilled water leachate test

This method, which is used by the Texas Commission on Environmental Quality (TCEQ), is intended to be used on dry solid waste that does not contain any free liquid. A 250 g (dry weight) representative sample is first placed in a 1500 mL Erlenmeyer flask, 1 L of deionized or distilled water is added to it, and the material is mechanically stirred for 5 min. It is allowed to stand for 7 days, after which the supernatant is passed through a 0.45 μm filter and further subjected to the appropriate analysis.

Other tests include ASTM C1308 Standard test method for accelerated leach test for diffusive releases from solidified waste and a computer program to model diffusive, fractional leaching from cylindrical waste forms (ASTM, 2008).

Field leachate tests with lysimeter

The lysimeter is a large catchment box typically 12 ft by 12 ft where the moisture entering the pavement and running through the base is captured for analysis in large collection tanks (Sauer, Benson, & Edil, 2005).

The European Committees for Standardization (CEN) including CEN TC 154 Aggregates and CEN TC 292 Characterization of Wastes have developed standard test methods for leaching tests. The leaching test for aggregates adopted in the United Kingdom, BS EN 1744-3, "Tests for Chemical Properties of Aggregates – Part 3; Preparation of Eluates by Leaching of Aggregates" is equivalent to the method developed by CEN TC 154 in 2002. The test consists of a single batch tank-leaching test over a duration of 24 h. The L/S ratio is 10 by mass with a material sample mass of 2 kg and particle size of <32 mm (1.26 in.). The leachate is distilled deionized water that is agitated using a dip stirrer. The pH of the leachate is controlled by the material sample. This test is designed to test unbound aggregates for the purpose of compliance testing. It is therefore a test to be used regularly to confirm that the batch of material is typical of that material as a whole and that it is suitable for the proposed use.

The CEN TC 292 approach has been to develop tests within three categories depending on the purpose: (i) characterization/leaching behavior tests used to obtain information on the short- and long-term leaching behavior and characteristic properties of materials; (ii) compliance tests—used to determine whether the material complies with specific reference values and is similar to the leaching behavior identified by the characterization tests; and (iii) on-site verification tests—used as a rapid check to confirm that the material is the same as that which was subject to the compliance test.

The CEN TC 292 compliance tests (prEN 12457 Leaching: Compliance test for leaching of granular waste materials and sludge: Part 1, 2, 3, and 4) are one- or two-batch tests with a duration of 6 or 24 h. The L/S ratio is 2 or 10 L/kg by mass for the single batch tests or 2 and 8 for the two-batch test. With particle size less than either 4 or 10 mm, the material sample has a mass of 100 g and a particle size less than either 4 or 10 mm. The leachate is distilled deionized water and the leaching vessel is agitated. The pH of the leachate is controlled by the material sample. The test is generally used as a compliance test, although the two-batch test does enable limited identification of the leaching mechanisms in operation.

CEN TC 292 are developing a suite of characterization or leaching behavior tests that are designed to address different aspects of leaching behavior. The tests cover availability, pH static, acid neutralization capacity, percolation, diffusion, and in situ simulation tests. Table 7.1 lists these tests with their working titles, project reference numbers, current status, and type of test (Hill, 2002).

Table 7.1 **Summary of leaching behavior tests under development by CEN TC 292**

Test title	Project reference	Current status	Type of test
Digestion for subsequent determination of aqua regia soluble portion of elements in waste	prEN 13657	Under approval	Availability
Influence of pH on leaching with initial acid/base addition	prEN 14429	Under approval	Aid neutralization capacity
Influence of pH on leaching with initial acid/base addition	–	Under development	pH static at a range of pH values
Upflow percolation test	prEN 14405	Under approval	Column test—accelerated leaching
Simulation of the leaching behavior of a waste material under specific conditions—downflow percolation test	–	Under development	In situ simulation
Dynamic leaching test for monolithic waste	–	Under development	Diffusion test

Data from Hill, A. (2002). Understanding the leaching behavior of slags, testing and interpretation. In: *Proceedings of the 3rd European slag conference, October 2–4, Keyworth, the UK*.

7.3 Special circumstances of slag use

Attention has been drawn to some special phenomena of slag product and performance, which sometimes raise concerns over slag use in certain applications. The subject slag may contain various levels of heavy metal or hazardous elements and have potential impact on humans and the environment.

7.3.1 Leaching limits

Various leaching tests are normally used to evaluate the acceptability of slag products and applications. Leaching limit values have been established. Table 7.2 is the European Council Directive on the Landfill of Waste leaching limit values for inert waste proposed in 2002. Table 7.3 presents the suggested Finnish leaching limits for Cr.

Table 7.2 **Leaching limit values for inert waste**

	L/S = 2 (mg/kg)	L/S = 10 (mg/kg)	C_0 (percolation) (mg/L)
As	0.1	0.5	0.06
Ba	7	20	4
Cd	0.03	0.04	0.02
Cr tot.	0.2	0.5	0.1
Cu	0.9	2	0.6
Hg	0.003	0.01	0.002
Mo	0.3	0.5	0.2
Ni	0.2	0.4	0.12
Pb	0.2	0.5	0.15
Sb	0.02	0.06	0.1
Se	0.06	0.1	0.04
Zn	2	4	1.2
Chloride	550	800	460
Fluoride	4	10	2.5
Sulfate	560	1000	1500
Phenol index	0.47	1	0.32
DOC	240	500	160
TDS	2500	4000	–

Data from Bialucha, R. (2005). New regulations in the field of environmental affairs. In: *Proceedings of the 4th European slag conference, June 20–21, Oulu, Finland.*

Table 7.3 **Suggested Finnish leaching values for the mineral materials used in earth construction**

Substance	Granular material Unpaved E_{max} (mg/kg)	Granular material Paved E_{max} (mg/kg)	Monolithic material E_{max} (mg/m^2)
Cr	2.0	5.1	550

Data from Roinnen, J., Vaara, N., & Ylimaunu, J. (2005). Quality control for stainless steel slag products—Especially the case of chromium leaching. In: *Proceedings of the 4th European slag conference, June 20–21, Oulu, Finland.*

7.3.2 Ferrous slags

Blast furnace slag and steel slag are generally environmentally friendly materials and can be used in selected applications in construction.

7.3.2.1 Blast furnace slag

Sulfur and stability

While it is reported air-cooled blast furnace slag (ACBFS) could contain high levels of sulfur, for most ACBFS, total sulfur content is below 1% as shown in Table 7.4. The total sulfur content ranges from 0.50% to 0.87%.

Table 7.4 Chemical composition of blast furnace slag

Chemical composition							Mineral composition			
No.	**CaO**	**SiO_2**	**Al_2O_3**	**MgO**	**Fe_2O_3**	**ΣS**	**C_2S**	**C_2AS**	**α-CS**	**CMS_3**
1	46.80	39.40	7.40	4.35	0.90	0.50	40–50	15–20	10–15	–
2	46.45	38.32	7.19	4.76	0.61	0.60	25–30	20–25	–	30–35
3	46.00	38.80	8.11	5.04	–	0.69	25–35	30–35	–	30–35
4	45.41	38.98	7.01	6.45	–	0.48	25–35	30–35	–	25–30
5	43.63	40.90	7.21	2.90	FeO 0.60	0.87	20–30	30–35	–	30–35
6	42.51	41.60	8.06	2.74	FeO 0.75	0.87	20–30	30–35	–	–
7	43.58	36.70	8.50	7.26	FeO 0.50	0.80	25–30	30–35	5–10	–
8	40.10	20.30	4.84	5.93	FeO 0.15	0.50	20–25	30–35	–	–

Data from Wang, G. (1993). Technical memorandum.

Stability

There could be a small amount of FeS, MnS and CaS, and f-CaO in blast furnace slag. Hydration of these substances could lead to volume expansion:

$$\mathrm{FeS} + 2\mathrm{H_2O} = \mathrm{Fe}\left(\mathrm{OH}\right)_2 + \mathrm{H_2S}$$

$$\mathrm{MnS} + 2\mathrm{H_2O} = \mathrm{Mn}\left(\mathrm{OH}\right)_2 + \mathrm{H_2S}$$

$$\mathrm{CaS} + 2\mathrm{H_2O} = \mathrm{Ca}\left(\mathrm{OH}\right)_2 + \mathrm{H_2S}$$

$$\mathrm{f\text{-}CaO} + \mathrm{H_2O} = \mathrm{Ca}\left(\mathrm{OH}\right)_2$$

The production of $Ca(OH)_2$, $Fe(OH)_2$, and $Mn(OH)_2$ accompanies increase of volume. It is very unlikely for CaS to transfer to $CaSO_4{\cdot}2H_2O$ and CaS_2O_3. Table 7.5 presents stability test results of some ACBFS. Table 7.6 presents some test results of potential expansion due to FeS, MnS. From Tables 7.5 and 7.6, it can be seen that ACBFS performs well in terms of stability under autoclave testing conditions.

In ambient temperature only calcium sulfate with half crystallized water ($CaSO_4{\cdot}½H_2O$) in saturated $CaSO_4{\cdot}½H_2O$ solution can transfer to $CaSO_4{\cdot}2H_2O$ (natural gypsum).

Tuffa and Thaumasite

Tuffa differs from Thaumasite ($CaSiO_3{\cdot}CaCO_3{\cdot}CaSO_4{\cdot}15H_2O$). The latter is formed during the hydration of silicate mineral in Portland cement, similar to calcium sulfoaluminate hydrate (known as Aft, ettringite, or cement bacillus). The mechanism of expansion of ACBFS is not as complicated as that of Portland cement hydration. When ACBFS is used as aggregate concrete, the total sulfur content should be <1.5%, and after 10 cycles if autoclave testing plus 25 cycles of freezing–thawing test, the loss of weight should be <1.17% (Wang, 1993).

Blast furnace slag in water

A water environment is the most susceptible to any adverse environmental effects associated with the use of blast furnace slag. Although incidents of water pollution arising from its use are rare, when they occur they tend to be long-lived and difficult to remedy. Griffiths (2002) reported some framework conducted in the United Kingdom. Elevated pH and oxygen depletion are usually associated with the incidents, as is the presence of a milky white suspension and the odor of hydrogen sulfide. The increase in pH can be attributed directly to the alkaline nature of the material but the deoxygenation can, at least in part, be attributed to bacterial action.

The British Environment Agency and the Quarry Products Association have produced clear, easily understood good practice guidance for the use of blast furnace slag. The guidance, which was targeted at construction professionals and agency field staff, concluded that blast furnace slag was suitable for use in the majority of cases; however, it should not be used in boggy or marshy ground, or below the water table.

Table 7.5 Stability test results of some ACBFS

Chemical composition %											
No.	**CaO**	**SiO_2**	**Al_2O_3**	**MgO**	**MgO**	**FeO**	**S**	**Aging time**	**No. of samples**	**Test method 8 atm**	**Results**
1	46.95	37.64	8.81	5.16	0.41		0.98	35 days	20	Autoclave	Good
2	45.95	38.70	9.17	4.99	0.53		0.92	53 days	20	Autoclave	Good
3	46.80	38.40	7.40	4.35	0.46	0.81	0.50	2.5 mos	20	Autoclave	
4	46.45	38.32	7.19	4.76	0.63	0.55	0.66	2.5 mos	20	Autoclave	Good
5	46.00	38.80	8.11	5.04	–		0.60	2.5 mos	20	Autoclave	Good
6	38.00	41.60	9.13	7.94	0.58		0.70	2.5 mos	20	Autoclave	Good
7	45.98	38.98	6.55	4.52	0.71	0.95	0.44	3 mos	20	Autoclave	
8	46.20	38.70	7.42	6.70	0.25	0.83	0.34	3.5 mos	30	Autoclave	
9	45.44	38.98	7.01	6.45			0.48	4 mos	20	Autoclave	Good
10	45.22	38.34	7.45	5.00	0.48	0.62	0.42	>3 years	30	Autoclave	Good
11	44.57	38.50	7.68	7.43				>5 years	20	Autoclave	Good
12	43.76	38.68	8.14	5.32	0.18	0.95	0.50	>5 years	20	Autoclave	Good
13	46.29	39.10	7.01	6.66				>5 years	20	Autoclave	Good
14	46.42	38.76	7.83	6.44				>5 years	20	Autoclave	Good
15	43.42	37.28	8.80	5.81	0.10	0.81	0.45	>5 years	20	Autoclave	Good

Data from Wang, G. (1993). Technical memorandum.

Table 7.6 Test results of potential expansion due to FeS, MnS

Chemical composition %								No. of samples	Water coaking				
No.	**CaO**	**SiO_2**	**Al_2O_3**	**MgO**	**FeO**	**M**	**S**		**0 days**	**6 days**	**90 days**	**1 day**	**3.5 years**
1	40.40	38.50	9.32	7.11	1.24	0.20	0.47	7	Good	Good	Good	Good	Good
2	46.80	39.40	7.40	4.35	0.81	0.46	0.50	25	Good	Good	Good	Good	Good
3	46.45	38.32	7.19	4.76	0.55	0.63	0.66	25	Good	Good	Good	Good	Good
4	38.60	41.30	9.13	7.91	0.29	0.58	0.70	25	Good	Good	Good	Good	Good
5	43.63	40.90	7.21	2.90	0.60	1.76	1.00	25	Good	Good	Good	Good	Good
6	43.18	39.30	6.80	6.85	0.60	0.21	1.50	25	Good	Good	Good	Good	Good
7	35.00	28.30	13.50	4.03	0.28	18.60	0.17	10	Good	Good	Good	Good	Good
8	34.50	26.20	23.50	6.02		6.81	0.33	20	Good	Good	Good	Good	Good
9	33.66	24.74	20.14	6.50		14.06	0.58	20	Good	Good	Good	Good	Good
10	36.80	24.90	21.40	6.70		6.26	0.87	20	Good	Good	Good	Good	Good
11	38.00	26.60	13.90	7.08		11.90	1.13	20	Good	Good	Good	Good	Good
12	40.01	27.62	14.35	5.14		8.78	1.15	20	Good	Good	Good	Good	Good
13	41.40	28.20	13.20	7.55		10.00	1.35	20	Good	Good	Good	Good	Good
14	40.39	28.60	15.26	5.04		7.07	1.38	20	Good	Good	Good	Good	Good
15	39.55	29.40	14.00	6.05		8.41	1.45	20	Good	Good	Good	Good	Good
16	38.99	27.60	14.71	5.75		8.53	1.49	20	Good	Good	Good	Good	Good

Data from Wang, G. (1993). Technical memorandum.

The guidance only applies to the use of modern blast furnace slag that is compliant with BS1047—Specification for ACBFS aggregate for use in construction. The slag is subject to stringent production quality controls, including a quality controlled natural weathering regime. The guidance sets out the background and context for the use of blast furnace slag and gives some description of its composition and properties. The main environmental considerations are (i) the material selection stage of the construction project will include a review of the environmental implications related to the use of any proposed aggregate source and the contractor will produce a method statement identifying all recognized measures to protect the aquatic environment; (ii) unbound slag should not be used in waterlogged or poorly drained areas, which will minimize any release of lime and sulfur compounds that could otherwise result in groundwater pH increase and oxygen depletion, and wherever possible, slag should not come into contact with the water table and where possible an unsaturated zone of around one meter should be maintained between the base of the fill and the water table; and (iii) where uhbound slag is used in the construction of large exposed areas such as vehicle parks and major carriageways, good practice should be followed to minimize the time the slag surface is exposed prior to overlay (Griffiths, 2002).

7.3.2.2 Steel slag

Slag use as armor stone

German Technical Terms of Delivery for Armor Stone provides a description how to assess the impact of basic oxygen furnace (BOF) slag, electric arc furnace (EAF) slag, and copper slag under surface water and groundwater conditions (Bialucha, 2005). Table 7.7 lists the maximum allowed limits. The eluate has to be prepared following EN 18744-3—Tests for chemical properties of aggregate—Part 3: Preparation of eluates by leaching of aggregates, with the modification that the material is not to be crushed below 32 mm but the actual particles size should be used. The typical parameters that are considered for steel slag are pH value, conductivity, and chromium.

Table 7.7 **Leaching limit values**

Industrially manufactured armour stones	**Maximum concentrations in demineralized water**			
	pH value	**Electrical conductivity (m S/m)**	**Concentration of chromium (mg/L)**	**Concentration of copper (mg/L)**
BOF slag	11.5	100	0.02	Not relevant
EAF slag	11.0	80	0.03	Not relevant
Copper slag	Not relevant	Not relevant	Not relevant	0.05

Data from Bialucha, R. (2005). New regulations in the field of environmental affairs. In: *Proceedings of the 4th European slag conference, June 20–21, Oulu, Finland.*

Gray staining on HMA surface

Gray staining was observed on localized HMA surface without other forms of distress, such as cracking or popout, upheaval, and blistering. It was also noticed that white coating exists on the surface of some steel slag aggregates.

Concern should be raised because **(i)** the main minerals in basic steel slag are C_3S, C_2S, CMS, C_3MS_2, and C_2F. If the steel slag is situated in a high-moisture environment to react with water during the aging (or during its service life), the following hydration reactions may occur:

$$2\left(3\text{CaO}\cdot\text{SiO}_2\right)+6\text{H}_2\text{O}=3\text{CaO}_2\cdot\text{SiO}_2\cdot3\text{H}_2\text{O}+3\text{Ca}\left(\text{OH}\right)_2\ \ \left(\text{easily leachable}\right)$$

$$2\left(2\text{CaO}\cdot\text{SiO}_2\right)+4\text{H}_2\text{O}=3\text{CaO}_2\cdot\text{SiO}_2\cdot3\text{H}_2\text{O}+\text{Ca}\left(\text{OH}\right)_2\ \ \left(\text{easily leachable}\right)$$

also including the hydration of f-CaO, if any:

$$\text{CaO}+\text{H}_2\text{O}=\text{Ca}\left(\text{OH}\right)_2\ \ \left(\text{easily leachable}\right)$$

The hydration of CMS, C_3MS_2, and C_2F is more complicated; however, under some circumstances, $Ca(OH)_2$ can exist and leach out. The hydrate $Ca(OH)_2$ can leach onto the surface of steel slag or of HMA surface. If the steel slag composite is in wet conditions for a relatively long time, calcium silicate hydrate (CSH) could also leach out. Both of these cases make the surface white or gray. It is known that this $Ca(OH)_2$ is not detrimental to HMA nor does it cause volumetric instability;

(ii) It is possible that other hydrates (eg, $Mg(OH)_2$) leach out onto the surface; this is the same situation as $Ca(OH)_2$, which is not harmful to volume stability.

(iii) The white–gray stuff is unlikely to be unhydrated f-CaO or f-MgO, because any f-CaO and f-MgO on the surface is unstable and easily to hydrate. Even if they are unhydrates f-CaO of f-MgO, they must be very small so as to leach out from pores of steel slag (<10,000 Å or 1 μm). It is unlikely and less important for f-CaO or f-MgO in tiny size to contribute to expansion.

(iv) Tests have been conducted in Australia on steel slag with white coating. Results indicated that there is no obvious difference in f-CaO content between the steel slags with and without white coating. Two steel slag samples were ground into powder finer than 75 μm and f-CaO content was tested. Results indicated little difference in the amount of f-CaO in the two steel slag samples (Wang, 1992).

Therefore, the occurrence of gray–white staining or coating is not necessarily related to expansion of steel slag and the final product; that is, HMA layers or base course. The explanation, therefore, is that the steel slag or HMA with gray–white staining or coating has undergone more hydration than others. The stability evaluation is dependent on f-CaO/f-MgO content, expansion test of the steel slag, and appearances if other forms of distress take place in the composite (Wang, 1992).

7.3.3 Nonferrous slags

7.3.3.1 Zinc slag

A leaching test has been conducted for unbound zinc slag aggregate and dense bitumen macadam containing zinc slag (WRAP, 2000). The results show (i) the quantities of constituents leaching from materials were all lower than the environmental quality standards for water quality standards limits in the United Kingdom except for lead and nickel; (ii) binding the zinc slag with asphalt binder significantly reduced the leached quantities; (iii) the quantities of materials leached from zinc slag bound by asphalt binder were similar to those leached from bound limestone and granite primary aggregates; and (iv) the test for zinc slag gave values consistent with disposal to an inert landfill.

The conclusions were drawn that (i) a laboratory leaching test of high-quality zinc slag asphalt with landfill acceptance tests has provided evidence that contaminants within the imperial smelting furnace (ISF) zinc slag are effectively bound up when the slag is used as an aggregate in asphalt; (ii) a properly designed and constructed road will minimize water ingress and percolation through its structure; and (iii) both these facts provide reassurance that contaminants in the ISF slag would be effectively immobilized in the matrix of an asphalt road structure in service.

There are no reasons why the road should not be recycled at the end of its life. However, assessment of the crushed asphalt materials against landfill acceptance criteria for granular waste has indicated that levels of lead leached from crushed asphalt containing ISF slag exceeds the limits for inert waste, placing the materials in the "nonhazardous" category. Based on these results, there should not be any environmental barrier to the use of ISF slag in these applications (WRAP, 2000).

7.3.4 Nonmelurgical slags

7.3.4.1 Radioactivity of phosphorus slag

As discussed in Chapter 4, phosphorus slag is a by-product from phosphorus element made by using the "dry method." EAFs are usually employed in the manufacture process. Chemical analyses of phosphorus slag have shown that the total amount of CaO and SiO_2 in phosphorus slag accounts for about 80% of total constituents. Therefore, calcium silicates are easily formed that make phosphorus slag possess cementitious property. The potential use of this slag can be raw materials for blend cement manufacture, white Portland cement, colored Portland cement, silicate block, expansive light aggregate, slag wool, granular aggregate, and ceramic tile. There are also some $A1_2O_3$, Fe_2O_3, and MgO and also a trace of P_2O_5 (usually <1%). The properties of water-quenched phosphorus slag are similar to those of granulated blast furnace slag. Table 7.8 shows typical chemical composition phosphorus slag.

X-ray diffraction analysis of phosphorus slag revealed that the main minerals in phosphorous slag are in the form of crystalline and consist mainly of pseudo-wollastonite with some calcium silicon oxide fluoride ($Ca_2SiO_2F_3$) and very little quartz.

Phosphorus is produced by melting a mixture of phosphate ore, silica, and carbon in an electric furnace; the phosphorus is recovered by condensation of its vapor. Iron, which results from the reduction of iron compounds in the furnace charge, combines with the phosphorus to form ferrophosphorus, which can be tapped off. The slag, which is formed from the unreduced constituents, is also tapped off.

The proportion of CaO, SiO_2, and $A1_2O_3$ must be controlled to obtain a slag of minimum melting temperature and low viscosity; this facilitates tapping and promotes the

Table 7.8 Typical chemical composition of phosphorus slag

	Sample 1	Sample 2	Sample 3
SiO_2	44.8	41.3	39.08
CaO	41.7	44.3	50.44
Al_2O_3	6.2	8.8	5.04
MgO	0.75	–	2.12
K_2O	0.9	1.2	0.10
Na_2O	0.5	–	0.17
MnO	0.3	–	–
FeO	1.4	–	0.21
S	0.4	–	0.15
F	2.8	2.8	–
P_2O_5	0.8	1.3	1.90
LOI	–	–	0.43
Total	100.55	99.50	99.64

Data from (Sample 1) FMC Corporation, Docatello, Idaho, USA; (Sample 2) Mantell, C.L. (1975). *Solid wastes: Origin, collection, processing and disposal*. New York, NY: John Wiley; (Sample 3) Nel, P.J. (1976). *There is more to slag than meets the eye*. Pretoria: National Building Research Institute, CSIR, R/BOU 573.

separation of slag from ferrophosphorus. If the percentage of alumina is increased, it is necessary to increase the ratio of SiO_2 to CaO by the addition of silica rock (Wang, 1993).

As most phosphate rocks, raw material for phosphorus making, contain between 30 and 200 ppm uranium, and radium content in radioactive equilibrium with the uranium (about 3–75 ppm), the thorium content of phosphate rock, based on a few reported analyses, is <10 ppm (Menzel, 1968). Most of the uranium comes out in the phosphorus furnace slag (Young & Altschuler, 1958).

In physics, radioactivity depends mainly on the following equation:

$$J = J_0 e^{-\mu d} \tag{7.1}$$

where J is the residual intensity of radioactivity; J_0 is the initial intensity of radioactivity; μ is the absorption coefficient, depending on the density of material, (matrix); and d is the thickness of matrix.

It can be seen that a certain thickness and density is important to reduce radioactivity. Due to the phosphorus, slag aggregate is usually used in a matrix and the thickness of the pavement or structure is considered to be sufficient to absorb the small amount of radioactivity.

Mixed aggregates (several different aggregates used together) should be used to minimize the radioactivity (this suggestion is not specially for phosphorus slag, because the radioactivity in phosphorus slag is low and can be neglected), and heavy slags with metallic content are to be chosen as aggregates, such as steel slag, and others (Wang, 1993).

Phosphorus slag has been used as aggregate in the United States; ceramic tile in South Africa and the United States; and cement manufacturing in China. One-hundred percent of the phosphorus slag has been utilized as highway construction materials in the country (FHWA, 2000), while in the United States this material has been limited to use in construction mainly due to radioactivity concerns.

7.3.4.2 Municipal incinerator ash and slag

A Danish testing protocol developed for the suitability of incinerator ash and slag for utilization is based on chemical parameters. The conditions include a $pH > 9$ for a 1% slurry of the material; alkalinity of >1.5 eqv/kg; metals levels as determined from a HNO_3 leach of $Pb < 3000$ ppm, $Cd < 10$ ppm, and $Hg < 0.5$ ppm. There are also restrictions on the placement of ash or slag that passes the criteria. Under paved roads, the maximum average thickness allowed is 1 m and the material must be above the highest groundwater table and more than 20 m from the nearest well. Under unpaved roads the same regulations apply except the thickness is restricted to 0.3 m. Subbase material has specific size requirements (<45 mm with a specified fines level), must have been stored for at least 1 month, have a loss on ignition (LOI) of <10%, and water content between 17% and 25%.

In France bottom ash and slag for construction utilization must meet criteria in relation to combustible content and leaching characteristics. The LOI content must be <5% and the requirements for a leaching test are given in Table 7.9. The material will still require ferrous removal, screening, and aging.

Table 7.9 **Requirements for bottom ash utilization—leaching (mg/kg unless noted)**

Total soluble solids	As	Cd	Cr^{6+}	Pb	Hg	SO_4	TOC
<5%	<2	<1	<1.5	<10	<0.2	<1.0%	<1500

Data from Chandler, A. J., Kosson, D. S., Eighmy, T. T., Sawell, S. E., Hartlén, J., van der Sloot, H. A., et al. (1997). Municipal solid waste incinerator residues. *Studies in environmental science: Vol. 67*. Amsterdam: Elsevier.

In the Netherlands the utilization of ash and slag in building materials is governed under the Soil Protect Act. This regulation covers both granular (aggregate) and monolithic (solids >50 cm^3 in size) and classifies materials according to chemical composition and leaching characteristics. If the material does not meet the requirements of one of the categories it cannot be placed in contact with the soil. Generally, material containing MSW incinerator ash of any form can be used if it meets the requirements but must be reclaimed after its useful life is over. Bottom ash and slag must be placed at least 70 cm above the groundwater table and should be isolated from infiltration. Leaching requirements for material are relaxed for placement in the marine environment so that Cl, F, and SO_4 leaching levels can be higher. The Dutch leaching limits are derived on the basis of a 1% increase in the average natural soil composition for the 1 m of soil under the construction after exposure of 100 years.

A certifying system for MSW incinerator residues use in constitution and technical specifications for the use in construction have been developed in the Netherlands (Chandler et al., 1997).

7.4 Summary

To use slag in construction applications, it is necessary to prove the material will not cause an unacceptable degradation of the quality of the geoenvironmental and hydrological environment surrounding the construction. An environmental assessment must be thorough, interdisciplinary, and as quantitative as possible. It is important that the policies and regulations are clear, concise, and quantified to reflect the real environmental outcomes and end products.

Enforcing legislation will not produce all the improvements required to significantly improve the environment. Governments have to engage their stakeholders and work with them to promote slag use, and enact performance- and risk-based regulations that will pave the way for the production of the jointly agreed guidance on the use of slag. Agencies need to develop principles for slag use that provide incentive for better performers and simplify existing legislation wherever possible. This approach will allow efficient use of the material in appropriate circumstances and provide an adequate level of protection for the environment.

Leaching is the main objective to measure and its main mechanisms can be categorized as (i) solubility, (ii) availability, or (iii) release-rate controlled. Careful thought and planning must be used when choosing a leachate test as each one has its own potential benefits and drawbacks. Leaching test data with respect to the proposed utilization scenario should be appropriately interpreted. Conclusions then can be drawn for the environmental acceptability and suitability of slag use in a specific environment.

Questions

7.1 Why is field performance-based regulation imperative for extensive and comprehensive utilization of slag?
7.2 What is the mechanism of leaching?
7.3 List three leaching test methods and compare their suitability.
7.4 What are the general requirements for the use of MSW slag in construction?
7.5 What needs to be considered in the use of phosphorous slag?
7.6 How to overcome institutional barriers in implementing the use of slag in construction?

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Unbound slag aggregate use in construction

8

8.1 Introduction

Aggregate is a broad category of particulate material mainly used in construction. Aggregate may be categorized into natural aggregate, such as sand, gravel, and crushed stone; and manufactured aggregate, such as slag, recycled concrete, and artificial aggregates. The term *granular* is also used to refer to the particulate material that contains any types of aggregate that may contain up to 35% particles passing the 75 μm (No. 200) sieve.

Unbound aggregates or granular materials are used in many horizontal transportation infrastructure applications to provide a stable foundation, bearing capacity, and other functions by the compacted granular particles, with or without binding agent, and help prevent differential settlement under the constructed facilities. The applications may include the use as base and subbase of highway pavement and airfield; ballast and subballast of railroad track; pipeline bedding or trench fill material; and other geotechnical applications such as embankment, engineering fill, subgrade or soil modifier, stone columns, and reinforced soil construction. Due to the relatively high hydraulic conductivity compared with most soils, coarse slag aggregate can function as foundation or pavement shoulder drains, and be used as filter media in sewage purification and lining for waterways.

To better understand the technical requirements for slag and end uses, it is necessary to briefly review the properties and requirements for aggregates and end products. The technical requirements for natural aggregates may vary depending on the specific applications that are normally provided by technical standards and specifications promulgated by different levels of government and organizations. Test methods are also provided in corresponding standard specifications. Examples of these technical specifications, test methods, and design guidelines include Standard Specification for Transportation Materials and Methods of Sampling and Testing, Part I: Specifications and Part II: Tests (33rd edition) and Provisional Standards (17th edition) of the American Association of State Highway and Transportation Officials (AASHTO); various current volumes of Sections 4 (Construction) and 11 (Water and Environmental Technology) of the Annual Book of Standards of the American Society for Testing and Materials (ASTM); AASHTO Guide for Design of Pavement Structures (1993), AASHTO Mechanistic-Empirical Pavement Design Guide (2011), and many other specifications by various professional organizations and national and local government agencies in the world. Other specifications include European Standards (EN) maintained by European Committee for Standardization (CEN) and German standards by the German Institute for Standardization (Deutsches Institut für Normung or DIN). In the last several decades, a number of specifications and test methods covering slag aggregate and its use have been developed. For example, British Standard Specification BS 1047:1983 for

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Air-cooled Blast Furnace Slag Aggregate for Use in Construction by the British Standards Institution (BSI, 1983); ASTM D4792, Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions; EN 1744-1: Tests for chemical properties of aggregates; and EN 12457-4: Characterization of waste. Relevant specifications are discussed and summarized in Chapter 15.

The construction industry consumes a tremendous amount of aggregate. Traditionally, the supply of aggregate had relied on the winning of natural deposits with crushing, sizing, grading, or washing in the forms of crushed, or combined with sand, gravel, or other mineral materials. In fact, natural aggregates are the most mined materials in the world. The size of the aggregate industry is huge; for example, in 2014 the United States produced 2.17 billion tonnes (2.39 billion tons) of natural aggregates including 911 million tonnes (1002 million tons) of sand and gravel and 1260 million tonnes (1386 million tons) of crushed stone (USGS, 2015), which include 71% limestone, 15% granite, 8.0% traprock, and 6.0% other minerals. The projected production of crushed stone and sand and gravel in 2020 will be 2.7 billion and 1 billion tonnes, respectively, in the United States (USGS, 2010).

Slag aggregate has become an important resource of aggregate to replace traditional natural aggregate in construction engineering. Although the use of iron blast furnace (BF) slag has a long history, the modern use of slag to replace natural aggregate was initially based on the consideration of the availability of natural resources, sustainable development, environmental protection, and the excellent engineering properties of slag. It has been reported that the resources of natural mineral aggregates of high engineering quality will ultimately become exhausted (Collins, 1976); the shortages of high-quality natural aggregates have been experienced and the resources are becoming less accessible in the United States and other countries (JCES, 1980; Lewis, 1982; USGS, 2010); and for environmental natural resource conservation purposes, the mining of sea sand has been banned in many Japanese cities (Nakagawa, 2007). As a consequence, the use of slag as a substitute for natural aggregate in civil construction is increasing.

Slag aggregate possesses good engineering properties which can be utilized in construction to enhance the performance of end products. Table 8.1 compares key physical properties and shows how air-cooled blast furnace slag (ACBFS) and basic oxygen furnace (BOF) slag differ from crushed limestone aggregate.

Table 8.1 **Comparison of BF slag and BOF slag aggregates with limestone aggregate**

	BF slag aggregate	BOF slag aggregate	Limestone aggregate
Apparent density	2.55	3.55	2.72
Water absorption (%)	4	1.3	0.7
Impact value dry (%)	34	7	19
Crushing value (%)	34	9	21
10% fines soaked-kN	85	360	160
Abrasion value (%)	5–7	1.5	8

Data from Dunster, A. M. (2002). Blastfurnace slag and steel slag as aggregate: A review of their uses and applications in UK construction. In: *Proceedings of the 3rd European slag conference*, *October 2–4*, *Keyworth*, *the UK*.

In addition, slag aggregate normally has a higher angle of internal friction, higher hardness value, and better aggregate impact and crushing value than natural aggregates. Because most of slag aggregate undergoes one or two steps of the crushing process, it has better angularity, elongation, and flakiness indexes than gravel aggregate; therefore, it can provide higher bearing capacity than sand and gravel do. Moreover, slag, as an energy containing material that shows hydraulic activity, can provide stronger and more durable products due to the binding resulting from hydraulic activity.

The use of ACBFS and steel slag has become a practical and potential construction method in pavement structures such as base, subbase, and for subgrade soil stabilization purposes (Akinwumi, 2014; Androjić & Dimter, 2012; Dayioglu, Aydilek, & Cetin, 2014; Dunster, 2002; Lykoudis & Liapis, 2010; Shen, Zhou, Ma, Hu, & Cai, 2009; Suer, Lindquist, Arm, & Frogner-Kockum, 2009; Tasalloti, Indraratna, Chiaro, & Heitor, 2015). Nonferrous and nonmetallurgical slags have been used in heavy civil construction projects, for example, nickel slag (Wang, Thompson, & Wang, 2011), lead slag (Buzatu, Talpoş, Petrescu, Ghica, & Jacob, 2014), tin slag (Yusof, 2005), and boiler slag (Griffiths & Krstulovich, 2002).

As enunciated in Chapter 6, to achieve current utilization for various slags and applications, it is important to have a good understanding of the technical requirements of traditional natural materials and their applications, including characterization, design, construction method, and specifications of the conventional material that slag may replace or incorporate with. A brief review of basic properties of aggregate relevant to bulk use and related specifications and test methods is presented in the next sections followed by practical uses and research of slags as unbound granular materials.

8.2 Technical requirements for aggregates and end products

Aggregate plays a very important role in the design and construction of civil infrastructure facilities; highway and airport pavements, for instance. Aggregate is the most important factor in the cost of pavement construction, accounting for up to 30% of the total cost.

In horizontal transportation construction, the functions that aggregate layers provide vary depending on the specific application. In highway pavement structures, the base course of a pavement lies immediately below the pavement surface and provides support for it and traffic. The base may consist of either a high-quality, unbound (unstabilized) aggregate layer or an aggregate layer stabilized with asphalt, cement, lime, or fly ash. In this chapter, bulk aggregate use with a small amount of binding or stabilizing agent is also included. The subbase, if present, is located below the base and serves a similar function as the base. The subbase is normally composed of materials of slightly lower quality and a wider gradation envelope than the base (refer to Fig. 9.5 in Chapter 9).

The importance of aggregate functions as an engineering material cannot be overstated. For example, for base course, subbase, filter bed, and leveling course lying between the compacted subgrade and the concrete slab or hot-mix asphalt (HMA) layers, an improper design, selection of the materials, and construction can lead to structural failure of the pavement. These layers serve a variety of purposes depending upon construction practices and the environment. They provide structural capacity to asphalt layers, drainage for Portland cement concrete slabs, and low susceptibility to frost. The characterization of slag is critical for its optimum use, which involves chemical, physical, mechanical, and environmental aspects. The chemical characterization comprises the determination of chemical composition, which may result in risks to the environment during production, handling, installation, and final use.

8.2.1 General requirements for aggregates

Aggregate specifications for various construction uses generally include gradation, degree of crushing, plasticity (liquid limit and plasticity index), durability and soundness, and abrasion resistance. Some specifications include a strength requirement such as a minimum California bearing ratio (CBR) value. The basic properties related to unbound aggregate use, including gradation, strength, shape, texture, and durability, are presented as below.

8.2.1.1 Gradation

Gradation of aggregate is one of the key factors in the success of aggregates use as an unbound granular material. The gradual gradation from coarse to fine is a key property of aggregates. Aggregate gradation affects the bearing capacity, stability, drainage, and frost resistance of base and subbase courses. Therefore, aggregates should be tailored to their proposed usage. There are three general types of aggregate mixtures that can be recognized with respect to fines, which is $<75\,\mu\text{m}$: (i) aggregates only, no fines; (ii) fines just filling the voids of aggregate fraction; and (iii) fines overfilling the voids of aggregate fraction.

In the first case the aggregate derives its strength from grain-to-grain contact of the particles. In this situation the granular material would be unstable unless it was confined, but it does provide excellent drainage and is completely nonfrost-susceptible.

In the second case, the aggregate also derives its strength from grain-to-grain contact of the particles. However, in this situation the granular material would be stable even if it is unconfined, because of the inherent cohesive properties of the fine content that fills the voids between the aggregate particles. Furthermore, the drainage is adequate and can be nonfrost-susceptible.

In the final case, the strength is derived from the grain-to-grain contact of the fines rather than of the aggregate particles; thus, a strength reduction occurs. The drainage characteristics of this granular material would be poor and it would be very frost-susceptible.

In most heavy civil construction the granular material falls between types one and two for best practice. Thus, a granular material should have sufficient fines to just fill the voids within the aggregate particles (Derucher, Korfiatis, & Ezeldin, 1998).

Aggregates may be typically classified into gap graded, uniformly graded, or well graded. Fig. 8.1 illustrates the three types of gradations. Generally, a well-graded material with a complete distribution of particle sizes will achieve higher density than a uniformly or gap-graded material. The maximum density of a graded aggregate generally is determined by the power grading law, Talbot equation, or Fuller–Thompson curve:

$$P = 100\left(\frac{d}{D}\right)^N \tag{8.1}$$

where, P is the percentage finer than the sieve, d is the sieve size in question, D is the maximum size aggregate to be used (top size), and N is the coefficient of adjustment, which adjusts the curve for fineness or coarseness.

Fig. 8.2 shows a typical plot using this formula at values of N equal to 0.3, 0.5, and 0.7. The maximum size of the aggregate is 25.4 mm (1 in.). Noting that a fine-graded material is represented by $N=0.3$ and a coarse-graded material is represented by $N=0.7$. Depending on specific particle characteristics such as angularity and shape, the maximum density for the aggregate generally exists when N is equal to 0.45–0.50. As the coefficient N increases, the percent passing sieve size "*d*" decreases. The maximum density curve is only an approximation, because the actual gradation may depend on the nature of the material. The Fuller–Thompson (Tolbot) curve is a valuable tool as a beginning point in designing aggregate blends for maximum density.

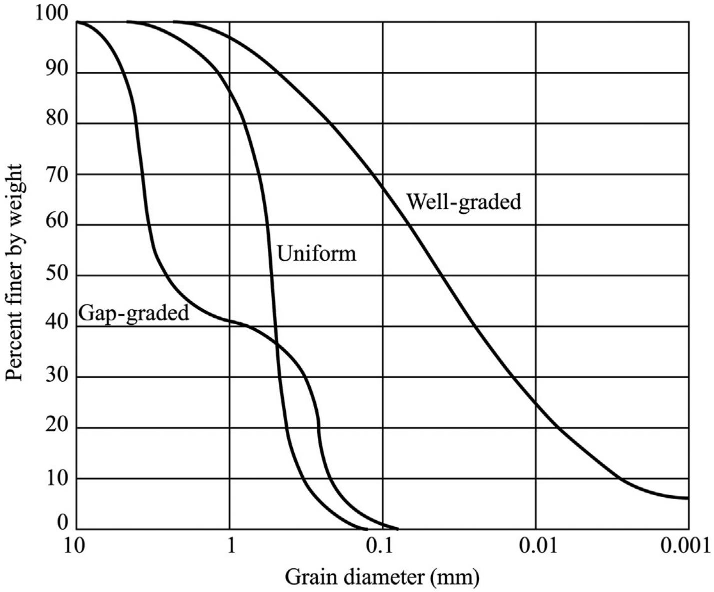

Fig. 8.1 Five types of gradation.

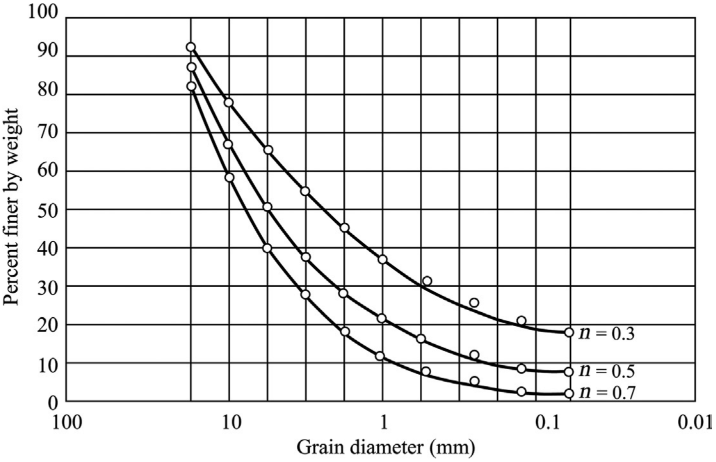

Fig. 8.2 Fuller–Thompson (Tolbot) curve.

Sometimes achieving maximum density is not the only factor to be considered in the specification for base and subbase. Local agency experience and tradition play a significant role in selecting actual gradation specification requirements.

As said, the percentage of material passing the 75 μm sieve (fines) is also a crucial parameter governing the behavior of aggregates. The optimal percentage of fines to achieve high density is higher than the value for high strength. Triaxial testing of base course aggregates found that depending on the specific gradation and state of stress, a critical fine content exists between 5% and 15%. Above this critical value, deformations under load increase very rapidly. Laboratory tests indicated that at a constant fines content, coarser gradations tended to rut less than finer ones (Barksdale, 1991). The plasticity characteristics of the fines in an aggregate are also critical for determining their behavior. For soils and aggregates to be used as fill, base or subbase courses, the plasticity index is an indicator of the material's potential strength loss in the presence of moisture. The CBR test is used as a simple index of soil strength as measured by penetration of a piston into the soil.

8.2.1.2 Strength

To resist the stress of repeated loads and to avoid aggregate degradation, unbound granular material must exhibit strength and toughness to function for its intended purpose. The strength of aggregate is a function of a variety of factors, including inherent strength of the particle and particle shape, density, and gradation. Aggregates must be strong enough to withstand handling during excavation, screening, transporting, and placement, and they also must be sufficiently strong to withstand loads while they are in use (Rollings & Rollings, 1996). In addition, the hardness of the aggregate adds strength to the bulk mixture. It is noted that most slag aggregates process high strength and hardness values.

Crushed aggregate particles achieve higher strength than rounded particles because of superior interlock of the crushed particles. Crushed particle shapes rather than rounded shapes improve rutting resistance of aggregates in aggregate base courses under pavements. Weak or friable particles are likely to undergo aggregate degradation.

8.2.1.3 Shape and texture

Angular shape and rough texture are preferred for unbound aggregate for structural use. The angularity contributes to aggregate interlocking, and a rough surface texture prevents movement of one particle upon another. Rounded particles tend to roll over one another as they do not interlock with one another. Smooth-textured aggregate particles allow slippage when they are in contact with each other. Thus, rounded aggregate with a smooth surface texture is least preferred for foundation usage (Derucher et al., 1998).

Ideally, aggregate particles should be cubical. Flat and elongated particles tend to cause problems with compaction, particle breakage, loss of strength, and segregation. Limits on flat and elongated particles are sometimes incorporated into specifications. Suggested upper limits on flat and elongated particles vary from 10% to 30% (Barksdale, 1991). Qualitatively, flat and elongated particles can cause problems, but there is no clear correlation between these specified limits on the particles and field performance.

8.2.1.4 Durability

The durability of aggregate particles is defined as their resistance to the accumulative effects of environmental and cyclical load conditions. Aggregate durability is affected by temperature, load, moisture conditions, chemical exposure, freezing, and thawing. A lack of aggregate durability leads to a breakdown of aggregate particles, resulting in an alteration in gradation and a resultant impairment of performance. Aggregates must be durable under the conditions to which they will be exposed. This may include being exposed to wetting and drying, freezing and thawing, abrasion, and impact during construction and while in service (Barksdale, 1991).

8.2.2 General requirements for end products

The general requirements for base and subbase of pavement and embracement are summarized as follows. For other final uses (eg, ballast and subballast) will be discussed in each section. It should be noted that special requirements are normally provided in construction project specifications that govern the quality control of the construction and the utilization.

8.2.2.1 Base and subbase of highway pavements

AASHTO Standard Specification, M147-65, Materials for Aggregate and Soil-Aggregate Subbase, Base, and Surface Courses (AASHTO, 2012a, 2012b) covers the quality and gradation of sand–clay mixtures; gravel, stone, or slag screenings; or sand, crusher run coarse aggregate consisting of gravel, crushed stone, or slag with or without soil mortar or any combination of these materials for use in the construction of subbase, base, and surface courses.

General requirements for coarse aggregate include (i) coarse aggregate retained on the 2.00 mm (No. 10) sieve shall consist of hard, durable particles or fragments of stone, gravel, or slag and materials that break up when alternately frozen and thawed or wetted and dried shall not be used; (ii) coarse aggregate shall have a percentage of wear, by the Los Angeles (LA) abrasion and impact test, of not more than 50%. Specific percentage of wear may be specified by the engineer, depending upon the materials available for the work.

General requirements for fine aggregate include (i) fine aggregate passing the 2.00 mm (No. 10) sieve shall consist of natural or crushed sand, and fine mineral particles passing the 75 μm sieve; (ii) the fraction passing the 75 μm sieve shall not be greater than two-thirds of the fraction passing the 0.425 mm (No. 40) sieve. The fraction passing the 0.425 mm sieve shall have a liquid limit not >25 and a plasticity index not >6.

All material shall be free from vegetable matter and lumps or balls of clay. The soil-aggregate material shall conform to the grading requirements of Table 8.2. The grading requirements for composite aggregate material can be specified by the engineer.

The ASTM standard specification for sizes of aggregate for road and bridge construction, ASTM Designation: D448-08 (ASTM, 2008), also provides the definitions for use in the construction and maintenance of various types of highways and bridges.

8.2.2.2 Graduation requirements of subbase materials

Materials for subbase shall conform to the requirements of Table 8.2 for Gradings A, B, C, D, E, or F. The type and grading desired shall be specified. Where local experience has shown that lower percentages passing the 75 μm sieve than are required in Table 8.2 are necessary for subbase materials to prevent damage by frost action, the engineer should specify such lower percentages.

8.2.2.3 Graduation requirements of base course materials

Materials for base course shall conform to the requirements of Table 8.2 for Gradings A, B, C, D, E, or F. The grading desired shall be specified. Where local experience has shown that lower percentages passing the 75 μm sieve than are required in Table 8.2 are necessary for base course materials in order to prevent damage by frost action, the engineer should specify such lower percentages.

8.2.2.4 Surface course materials

Materials for surface course shall conform to the requirements of Table 8.2 for Gradings C, D, E, or F. The gradings desired shall be specified. Where it is planned that the soil-aggregate surface course is to be maintained for several years without

Table 8.2 Grading requirements for soil-aggregate materials

Sieve designation		Mass percentage passing					
Standard (mm)	**Alternate**	**Grading A**	**Grading B**	**Grading C**	**Grading D**	**Grading E**	**Grading F**
50.0	2 in.	100	100	–	–	–	–
25.0	1 in.	–	75–95	100	100	100	100
9.5	3/8 in.	30–65	40–75	50–85	60–100	–	–
4.75	No. 4	25–55	30–60	35–65	50–85	55–100	70–100
2.00	No. 10	15–40	20–45	25–50	40–70	40–100	55–100
0.425	No. 40	8–20	15–30	15–30	25–45	20–50	30–70
0.075	No. 200	2–8	5–20	5–15	5–20	6–20	8–25

Data from AASHTO (2012a). Standard specification for materials for aggregate and soil-aggregate subbase, base, and surface courses. AASHTO designation: M 147-65 (2012); AASHTO (2012b). Materials for embankments and subgrades. standard specification for AASHTO designation: M 57-80 (2012).

bituminous surface treatment or other superimposed impervious surfacing, the engineer should specify a minimum of 8% passing the 75 μm sieve in lieu of the minimum percentages shown in Table 8.2 for Gradings C, D, or E, and should specify a maximum liquid limit of 35 and plasticity index range of 4–9.

8.2.2.5 Moisture content

All materials shall contain moisture equal to or slightly below the optimum necessary to ensure that the design density requirements are obtained when materials are compacted.

8.2.2.6 Embankment

AASHTO Standard Specification, M57-80, Materials for Embankments and Subgrades (AASHTO, 2012b) covers materials for use in the construction of embankments and subgrades. General requirements for the materials used in embankment construction includes (i) materials shall be free from detrimental quantities of organic material, such as leaves, grass, roots, and sewage; (ii) materials obtained from cuts or borrow areas shall conform to one of the following requirements:

> *In embankments*: Materials classified in the A-1, A-2-4, A-2-5, or A-3 groups as in AASHTO M 145 (Standard Specification for Classification of Soil and Soil-Aggregate Mixtures for Highway Construction Purposes) shall be used when available and shall be compacted to the depth specified to not <95% of the maximum density per AASHTO T99 (Standard Method of Test for Moisture-Density Relations of Soils Using 2.5 kg Rammer and a 305 mm Drop). If material of this character is not available and materials from the A-2-6, A-2-7, A-4, A-5, A-6, or A-7 groups must be used, special attention should be given to the design and construction of the embankment. Materials from these groups shall be compacted to not <95% of the maximum density and within two percentage points of the optimum moisture content per AASHTO T 99.
>
> *In subgrades*: Materials classified in the A-1, A-2-4, A-2-5, or A-3 groups as shown in M 145 shall be used when available and shall be compacted to the depth specified to not <95% of the maximum density per AASHTO T99. Materials in the A-2-6, A-2-7, A-4, A-5, A-6, or A-7 groups may be used if compacted to the depth specified to not <95% of the maximum density and within two percentage points of the optimum moisture content per AASHTO T 99.

Density percentage requirements may be specified in terms of AASHTO T180, if the resultant density and optimum moisture content are comparable with AASHTO T99 under the above conditions.

8.2.3 Measurement of the properties of aggregate

Testing of aggregates may be performed on in situ materials in an attempt to identify acceptable quarries and natural and slag aggregate sources prior to development of the aggregate source, or it may be done on bulk (stockpiled) materials that have already been removed from their original source. In either case, correct sampling techniques must be used. Appropriate sampling of aggregates is essential for obtaining laboratory testing results that accurately reflect the properties of the aggregates of interest.

Tests concerning the general quality of aggregates used for unbound granular are briefly presented next.

8.2.3.1 California bearing ratio

California bearing ratio (CBR) was initially developed and used as the basis for an empirical flexible pavement design procedure in 1929 by the California Highway Department (Rollings & Rollings, 1996). It is still used for pavement design and as a standard basis of comparison for validating less well-accepted design procedures in many countries around the world. The CBR test can be used to test laboratory compacted samples or samples taken from the field; it also can be run on in situ field samples. Laboratory compacted samples are tested to determine the design CBR for a particular material. The purpose of running the CBR test on field samples is to determine as-placed or in situ conditions in compacted fill. The test is most appropriate and gives most reliable results for fine-grained soils, but it is also used to characterize the strength of soil-aggregate mixtures (eg, subbases) and unbound aggregate base courses. The CBR test provides an index of strength, but it is not a strength measurement, as are the unconfined compression, triaxial, and direct shear tests. The CBR test measures the resistance to penetration and compares those results with a standard set of values to determine the CBR value for that particular soil. The test involves pushing a piston of 3 in.^{2} end area into a soil specimen at the specified rate of 0.05 in./min. The unit load is recorded at each 0.10 in. of penetration up to a total deformation of 0.5 in. The loads at 0.1 and 0.2 in. of deformation are then compared with the loads required to cause equal penetrations into a standard well-graded crushed stone specimen containing three-fourths in maximum sized particles.

When evaluating the CBR test, the CBR at 0.1 in. of penetration into the soil is usually taken for use in design. This is typically the largest value obtained for a particular test, as the CBR generally decreases as penetration increases.

Field CBR test procedures are essentially the same as in the laboratory except that the sample is tested at in situ moisture conditions. For the field test, it is critical that the testing device be plumb and that the deflection dial is fastened well outside the loaded area. Procedures for specimen preparation and CBR testing are given in ASTM D1883: Test Method for CBR of Laboratory-Compacted Soils.

8.2.3.2 Abrasion resistance

The LA abrasion test is the most widely used test to specify abrasion resistance and mechanical soundness of aggregate. In this test, a sample of aggregate is placed in a hollow revolving drum with a charge of steel balls. As the drum rotates, a shelf inside the drum lifts and then drops the aggregate and steel balls on each revolution.

The Los Angeles resistance is expressed as the percentage loss finer than the 1.7 mm (No. 12) sieve after 500 revolutions of the drum. This test gives an indication of the impact toughness of the aggregate. In a general sense, it identifies aggregates that may be susceptible to abrasion under traffic or physical degradation during excavation, handling, and placement. Generally, a LA abrasion test result of 40% or less is considered satisfactory for aggregates, although sometimes a more restrictive value of 30% is used for aggregates in surfacing for critical facilities such as airports. Aggregates within the pavement structure such as in base courses are sometimes allowed to have LA abrasion values as high as 50%. Even though aggregates within the pavement structure may not be exposed directly to the abrasion of traffic, they may degrade on handling, placement, and compaction with a resulting increase in fines and reduction in strength if the LA abrasion results are too high. The LA abrasion test exposes the aggregate to considerable impact, and brittle aggregates may degrade more in this test than they would under actual construction and traffic conditions. For example, BF slag and some granites often perform poorly in this test but perform well in practice.

Consequently, results of this test should be correlated with local experience. An aggregate meeting this test is probably sound and resistant to physical degradation and abrasion. An aggregate failing this test may still be suitable, and further evaluation of its past history of use, hardness, and petrographic characteristics may be justified (Barksdale, 1991).

Procedures for specimen preparation and LA abrasion testing are given in ASTM C131: Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine; and ASTM C535: Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.

8.2.3.3 Micro-deval test

The micro-deval abrasion test is a test of coarse aggregate to determine abrasion loss in the presence of water and an abrasive charge. Many aggregates are more susceptible to abrasion when wet than dry, and the use of water in this test incorporates this reduction in resistance to degradation in contrast to some other tests, which are conducted on dry aggregate. The test results are helpful in evaluating the toughness/abrasion resistance of coarse aggregate subject to abrasion when adequate information is not available from service records. The micro-deval abrasion test is useful for detecting changes in properties of aggregate produced from an aggregate source as part of a quality control or quality assurance process.

Procedures for specimen preparation are given in ASTM D7428: Standard Test Method for Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus; and ASTM D6928: Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus.

8.2.3.4 Freezing and thawing test

If the pores of an aggregate are filled with water such that there is insufficient space to allow the expansion of the water upon freezing, the aggregate is considered critically saturated. If frozen in this condition, degradation of the aggregate may occur. The vulnerability of aggregates to freezing is a function of the saturation, aggregate size, pore structure, permeability, and tensile strength of the aggregate. Some agencies expose an aggregate to repeated freezing and thawing to evaluate durability. Results are variable, and specific test procedures between agencies may vary.

Procedures for specimen preparation and freezing and thawing testing are given in AASHTO Standard Method of Test for Soundness of Aggregates by Freezing and Thawing, AASHTO T 103-08 (2012).

8.2.3.5 Sulfate soundness test

This test is also widely used as a durability test. This test subjects aggregate samples to repeated wetting and drying with either a sodium or magnesium sulfate solution. Conceptually, the growth of the sulfate crystal in the aggregate pores due to repeated wetting and drying is analogous to the growth of an ice crystal in the aggregate pores due to freezing and thawing. Although the direct freezing and thawing test of aggregates and the sulfate soundness test cannot directly predict field durability, they may be useful for evaluating relative aggregate performance, at least on a regional basis. An aggregate should not be rejected for use on the basis of these tests alone if it has a proven local record of performance under conditions similar to its anticipated use.

In this procedure a specific weight of an aggregate having a known sieve analysis is immersed in a solution of sodium or magnesium sulfate for 16–18 h. Next, it is placed in an oven at 110° C (230° F) and dried to constant weight. The procedure is repeated for the desired period (usually 5 or 10 cycles); the sample is cooled, washed, and dried to constant weight; then sieved, weighed, and recorded as the percent of weight lost.

Procedures for specimen preparation and sulfate soundness testing are given in ASTM C88: Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate.

It should be noted that no single test correlates well with the durability of aggregates in the field when exposed to natural weathering processes or abrasive action. Consequently, laboratory durability tests are probably best considered as screening tests. Field service records of an aggregate's performance under similar exposure conditions and field investigations of the natural soils formed by this rock's weathering are probably the best indicators of future performance.

8.2.4 Construction procedures

Base and subbase are important pavement structure components to support and distribute loadings and protect surface layers. Base and subbase materials should be placed on well-drained, uniform, and properly compacted subgrade. The major steps of base and subbase construction are as follows.

8.2.4.1 Subgrade preparation

Before placing subbase and/or base courses, unsuitable subgrade soils with low CBR values should be corrected. The CBR-based subgrade soil category is presented in Table 8.3.

Proof rolling is sometimes effectively used to evaluate the subgrade by using a heavily loaded dump truck in both directions. Areas that deform excessively should be undercut and replaced with suitable backfill or stabilized.

Table 8.3 **Soil support categories**

CBR	Support category
15+	Excellent
10–14	Good
6–9	Fair
5 or less	Poor

Data from Barksdale, R. D. (ed.) (1991). *The aggregate handbook*. Washington, DC: Nationals Stone Association.

8.2.4.2 Spreading the base materials

The aggregate should be brought to the job at the specified gradation and required moisture content. The aggregate should be placed in layers to a uniform loose depth no >200–250 mm (8–10 in.), and compacted to the specified density using a minimum of blading to avoid segregation. Spreading can be accomplished by mechanical spreaders, mechanical stone boxes, or end dumping. In any method, the potential for segregation should be minimized.

8.2.4.3 Compaction of aggregate base

Proper compaction equipment must be chosen and used efficiently. Some types of compactors achieve the necessary compaction with less effort than other methods. Certain types of compaction equipment include (i) vibratory compaction by the self-propelled vibratory roller; (ii) pneumatic-tired roller (rubber-tired roller) that is commonly used on cohesionless soils as well as aggregate bases; and (iii) heavy smooth steel-wheeled rollers that are often used on stone base construction, either for initial breakdown rolling close behind the spreader or for final finishing teamed with a motor grader.

Vibratory compaction by the self-propelled vibratory roller is the most efficient and most versatile method for stone base construction. The first several passes of any vibratory roller should be in the “static” mode. This procedure acts as a breakdown roller for better control of initial compaction prior to vibratory rolling to required density. The drum weight and amplitude of movement should be adjusted according to lift thickness and the strength of the material beneath the lift. High amplitudes of vibration should not be used on a thin lift, especially if the lift is being placed on a weak subgrade. Repeated passes at high amplitude tend to fracture particles of aggregate, producing degradation and a change in the particle size distribution. Pneumatic-tired roller (rubber-tired roller) effectiveness on crushed stone bases is dependent upon the pressure and kneading action of the tires. Pneumatic-tired rollers have the advantage of achieving uniform density even when the underlying surface is uneven. Steel-wheeled rollers are less effective than vibratory rollers in achieving uniform compaction of base layers >100–150 mm (4–6 in.) thick.

8.2.4.4 Field compaction control

The laboratory compaction result is used for controlling compaction in the field. The moisture–density relationship test (Proctor test) should be conducted for the same materials used on site according to AASHTO T180: Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop, and is specified as the required compaction level in percentage to be achieved in the field. The moisture content must be within a certain range to be able to achieve the required density in the field. Project construction specifications normally define a final target density as a percentage of the standard compacted density established for a particular class of service required. For heavy-duty traffic, 100% compaction of the maximum dry density (MDD) may be considered adequate in the top 200–300 mm (8–12 in.) below the first layer of the pavement structure.

8.2.4.5 Field moisture control

Compaction of any soil or graded aggregate can only be accomplished when the moisture content of the material is within the allowable range of moisture. Ideally, moisture should be uniformly distributed through the base material as it is produced and stockpiled at the plant or as moisture is introduced as the material goes through a pugmill mixer just prior to loadout for delivery to the job. This moisture content must be maintained until the target density has been reached. If the moisture is too low, water must be added using water trucks with spray nozzles. If the moisture content is too high, water must be removed by either air-drying naturally or other means.

8.2.4.6 Effective compaction control

Aggregate base must be compacted to the specific target density established either in the laboratory or on a field control strip. The same gradation of aggregate must also be used throughout the job and maintained within close tolerances as required. Any change in material source or processing requires submission of a new job mix formula and the establishment of a new target density.

8.2.4.7 Field density tests

To assure adequate compaction, field testing is conducted for in-place density. Density tests are made most rapidly by means of a nuclear moisture-density gage. Preferably, the nuclear moisture-density gage should be operated in the direct transmission mode to reflect the average wet density of the full depth of a lift. The backscatter method is influenced mainly by the top 25 mm (1 in.) of material immediately beneath the detector (Barksdale, 1991). The base should be compacted in the field to 100% of AASHTO T180 density. Fig. 8.3 presets the nuclear moisture-density gage and its work principles. It is important to perform correlation tests on every site when slag aggregate or other nonconventional materials are used as some metallic matters and materials with hydrogen ions may affect the readings.

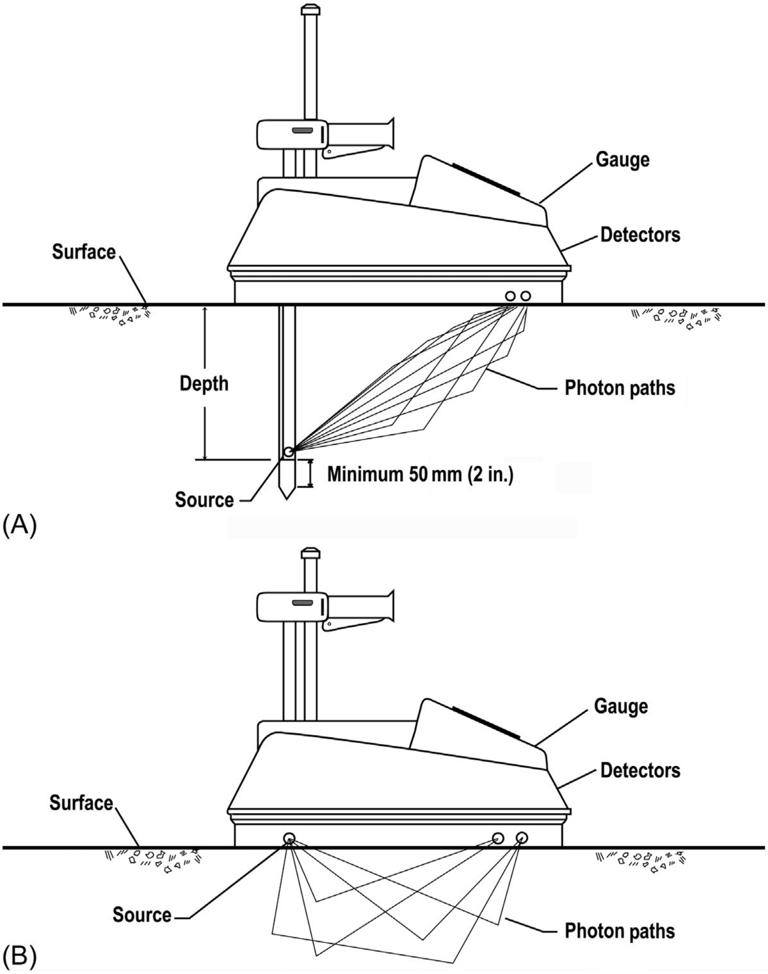

Fig. 8.3 Nuclear moisture-density gage. (A) Direct transmission mode and (B) backscatter mode. Courtesy of Troxler Electronic Laboratories.

8.3 Use of unbound slag aggregate in construction

The overall use of ACBFS is relatively well known for a range of highway construction applications including unbound granular base and subbase, which are regulated by technical specifications. Standard specifications for ACBFS use in road construction as an aggregate was enacted in some countries in the 1970s; for instance, British Standard Specification BS 1047:1983 Air-cooled Blast Furnace Slag Aggregate for Use in Construction was established in 1974; Japanese Industrial Standard JIS A5015: Iron and Steel Slag for Road Construction was enacted in 1979 and has undergone four revisions before becoming the current edition. Technology has been developed since then and utilization has been expanded to steel slag and nonferrous and nonmetallurgical slags. In contrast to ACBFS, which is volumetrically stable and straightforward in its construction uses, steel slag from a BOF and electric arc furnace (EAF) contains free (unhydrated) lime (CaO) and periclase (MgO) that can result in volumetric instability (expansion) that must be dealt with through appropriate steel slag aging, testing, and quality control to ensure its appropriate use in construction. Each specific slag, in terms of type, process, and source, should be fully evaluated for each proposed use, given the significant differences in properties that can be involved and the specific performance requirements for bulk uses.

From the experience in the last few decades on the development of the use of air-cooled slag in construction, the main focuses have been placed on (i) the general properties and special characteristics of a specific slag; (ii) environmental impact; (iii) economic benefit for a specific project and use; (iv) volume expansion mitigation for steel slag, and probably other ferrous slags.

8.3.1 Granular base and subbase

ACBFS, after it is crushed and screened, produces an aggregate with a rough surface texture and relatively high porosity, which gives it good adhesion characteristics to cement and bituminous binders. Basic oxygen steel slag is relatively nonporous and produces a high-density aggregate with high crushing strength. The processed material is denser and stronger than BF slag. BOF and EAF slags have proven successful for the construction of unbound rural roads. Recently, road trials have been conducted in EAF and ladle slag use as road base and subbase. Ladle slag contains a high content of lime contributing to quick self-hardening, which results in a higher load-bearing capacity and a lower dust generation on rural roads and surrounding areas. Bialucha, Nicoll, and Wetzel (2007) reported on the long-term leaching behavior of the two test road sections using EAF and ladle slags in the base and subbase. The subject test road was built with two different aggregates or mixtures: (i) 40 cm of natural stone as the base and 10 cm of a mixture of EAF and ladle slag (1:1) in the unbound surface layer; and (ii) 50 cm 100% EAF slag. The comparison of the two materials and their combination are summarized in Table 8.4. All materials are characterized concerning technical qualities, mineral and chemical composition, and leaching properties.

Table 8.4 **Materials used in two rural test road sections**

		Section 1	**Section 2**
	Thickness	**Materials**	
Unbound surface course	10 cm	1:1 EAF and LD slags (0–16 mm)	1:1 EAF and LD slags (0–16 mm)
Unbound base course	40 cm	Natural crushed stone (0–32 mm)	EAF slag (0–32 mm)

Data from Bialucha, R., Nicoll, R., & Wetzel, T. (2007). Long term behavior of steel slag used for unbound rural roads. In: *The 5th European slag conference*, *September 19–21*, *2007*, Luxembourg.

Laboratory and road tests were carried out to investigate the leaching behavior of the slag materials. Suction cups were used to collect the seepage water in the middle and the edge zone of both sections with either EAF slag and natural aggregate in the road base as well as 5 m (16.4 ft.) to the side of the test road. The results have proved that no environmentally relevant amounts of heavy metals or salts had leached out of the material and have influence on the groundwater. Also by using the slag materials, no appreciable amounts of dust covering the road and surrounding areas was observed. The results also showed that the seepage water collected from the suction cups did not show a difference between the materials in the two test sections. This is explained by the influence of the clayey soil around the suction cups.

Vazquez et al. (2010) reported on test road sections in both unbound and cement stabilized base courses using EAF and ladle slag. The unbound granular consists of two layers of EAF and ladle slag mixtures. Each layer is 20 cm (8 in.) thick and aged independently for three months. The materials used are summarized in Table 8.5.

Table 8.5 **Unbound EAF and ladle slags for test sections**

Pavement structure layers	Thickness	Slag materials (expansion rate of mixture 1.18%)	
		EAF slag–3 month aging; expansion rate 0.93%	Ladle slag–3 month aging; expansion rate 3.34%
Base	20 cm	70–80%	20–30%
Subbase	20 cm	70–80%	20–30%

Data from Vazquez, E., Barra, M., Perez, F., Alavedra, P., Scheibmeir, E., & Bou, M. (2010). Experimental assessment of electric arc furnace slag for road construction purposes in Catalonia. In: *Proceedings of the 6th European slag conference*, *October 20–22nd*, *Madrid*, *Spain*.

All the expansion test results correspond to 168 h of testing. An average expansion rate on the construction site showed 2.25%, which was similar to the results tested in the laboratory. The bearing capacity tracked for 6 months in various points of the test road showed a continuous increase of the modulus.

The cement stabilized section consisted of 10 cm (4 in.) natural subbase course, 30 cm (12 in.) of hydraulic bound base course, combining 10 cm of natural soil, 20 cm (8 in.) of EAF and ladle slag together with 2% of cement and 16 cm (5/8 in.) bituminous mixture (three layers) was constructed. Table 8.6 presents the cement stabilized pavement structure. Studies also showed how mixed use of EAF and ladle slag can reduce the binding agent required in stabilized base and subbase course. The results showed that the minimum compressive strength required can be obtained by adding 2% of cement. The mixture of natural soil and EAF and ladle slag presented a higher strength than the slag alone. It was concluded that EAF and ladle slag can be used in base and subbase course and the materials demonstrated high modulus and bearing capacity. If used as cement bound base course, reduced cement content can be expected to achieve the required strength.

One of the nonferrous slags, nickel slag, was successfully used in highway construction (Wang et al., 2011). A laboratory evaluation of the use of air-cooled nickel slag

Table 8.6 Cement stabilized pavement structure

Pavement structure layers	Thickness	Materials	Notes
Surface	16 cm	Hot-mix asphalt	In three layers
Base	30 cm with 2% cement	20 cm (67%) EAF and ladle slags (expansion rate of mixture 1.18%) 10 cm (33%) natural soil	EAF slag–3 month aging with expansion rate of 0.93%; ladle slag–3 month aging with expansion rate of 3.34%
Subbase	10 cm	100% natural stone	

Data from Vazquez, E., Barra, M., Perez, F., Alavedra, P., Scheibmeir, E., & Bou, M. (2010). Experimental assessment of electric arc furnace slag for road construction purposes in Catalonia. In: *Proceedings of the 6th European slag conference, October 20–22nd, Madrid, Spain*.

was conducted based on the nickel slag produced at the Falcondo facility in Bonao, Dominican Republic, before use in construction. Nickel slag is a coproduct of ferronickel production that is solidified under ambient atmospheric conditions. Laterite ore is open-pit mined and then processed through a preparation, reduction, and electric furnace melting process. Molten slag is removed from one end of the furnace and ferronickel is removed from the other end for refining and shipment. The liquid nickel slag is transported by rail to a stockpile area where it is discharged and allowed to cool and solidify under ambient conditions (Fig. 8.4). This air-cooling results in some fragmentation into sizes conveniently suitable for riprap, armor stone, and gabion stone

Fig. 8.4 The dumped molten ferronickel slag is fragmented by "thermal shock." during ambient cooling in the slag storage area (A).

Continued

Fig. 8.4 Continued. Fragmented sized and crushed and screened to a wide range of gradations for highway construction uses (B).

use. The fragmented air-cooled nickel slag can be crushed and screened for a variety of construction aggregate purposes, as engineered fill, granular base and subbase, and HMA coarse and fine aggregate.

Table 8.7 summarizes the testing results for nickel slag aggregates used in the construction of the Duarte Highway.

Table 8.7 **Physical properties of nickel slag aggregate**

		Test results (coarse)		Test results (fine)	
Test		**Nickel slag I**	**Nickel slag II**	**Nickel slag I**	**EP Slag II**
Bulk relative density (BRD)		3.157	3.192	3.182	3.306
Absorption, %		1.11	1.00	1.25	0.73
Flat or elongated particles, %	3:1	4.5	16.7	34.6	31.8
	4:1	1.1	9.5	22.8	19.8
	5:1	0.5	1.5	9.0	6.1
Unconfined freeze thaw, % loss		0.8	0.2	49.8	48.3
Crushed content, one face, %		100	100	98.2	89.0
Micro-deval abrasion, % loss		3.7	7.7	–	–
Los Angeles abrasion, % loss		13.3	22.0	Not plastic	Not plastic
Magnesium sulfate soundness, % loss		0.5	1.2	1.5	7.7
Sand equivalent		–	–	98	98

Data from Wang, G., Thompson, R., & Wang, Y. (2011). Hot mix asphalt that contains nickel slag aggregate—Laboratory evaluation of use in highway construction. *Journal of the Transportation Research Board*, *2*(*2208*), 1–8. doi:10.3141/2208-01.

Based on considerable practical positive international experience as well as satisfactory local use for several years, leachate characterization, mineralogical evaluations, and the favorable comprehensive accelerated stability and durability testing, nickel slag was given full project approval for engineered fill, granular subbase, and HMA aggregate use. Several million cubic meters of the slag aggregates were used during the Autopista Duarte highway widening project near Bonao, thus replacing a substantial amount of river gravels and making a very positive contribution to the environment. Figs. 8.5 and 8.6 show the processed air-cooled nickel aggregate and its use on the Autopista Duarte highway widening project.

Fig. 8.5 Processed nickel slag aggregate.

Fig. 8.6 Blended crushed river gravel and Falcondo aggregate (nickel slag) granular base use for Autopista Duarte widening near Bonao.

8.3.2 Ballast and subballast

Air-cooled BF and steel slag have been used as railroad ballast and subballast products for a long time (NSA, 2015) and have proven to be excellent railroad ballast materials.

The railroad ballast layer is the uppermost aggregate layer in a railroad track structure and is located immediately beneath and surrounding the ties. The layer underlying the ballast is called the subballast. Subballast layers are not always utilized in track construction.

The functions of ballast include (i) transfer of the imposed loadings uniformly to the subgrade soil (roadbed) at a stress tolerable for the particular material in the roadbed; (ii) provide uniform support for the ties with the necessary degree of elasticity and resilience to absorb vibrations and shock; (iii) anchor the track in place and resist vertical, lateral, and longitudinal movement; (iv) provide immediate free drainage and prevent the growth of vegetation; and (v) resist aggregate degradation due to physical forces exerted by traffic and maintenance equipment and environmental factors such as freeze-thaw and wet-dry.

Ballast has been produced from open hearth slag and BOF and EAF slag. Now EAF slag predominates in the marketplace. Steel slag consists principally of calcium silicates and calcium alumino-ferrites and fused oxides of calcium, iron, magnesium, and manganese. The compositions vary with the type of furnace, composition of furnaces charges, grades of steel produced, and individual furnace operating practices. Steel slags have hard, dense, angular, and roughly cubical particle sets to form a solid but permeable mass.

The standard ballast aggregate sizes are specified by general and railroad specifications including American Railway Engineering Association (AREA) Specification for Prepared Slag, Stone and Gravel Ballast; Federal Specification SS-S-449: Slag and Stone, Crushed for Railroad Ballast; and Canadian National Railways (CNR) Specification 12-22, Slag Ballast. The standard aggregate gradations following the ASTM specification ASTM D448 are incorporated into a more detailed specification for a specific application of railroad ballast. For example, ASTM No. 4 gradation is the equivalent of AREA No. 4 ballast gradation.

8.3.2.1 Properties of slag ballast

Characteristics such as specific gravity vary by type of slag and source. The producers in the particular project area provide data on their specific product.

Durability

Slag ballast and subballast are highly resistant to weathering action such as freezing and thawing. Sulfate soundness losses (ASTM C88) are low for steel slag. LA abrasion testing shows steel slag ballast to be a hard aggregate, minimizing degradation from heavy traffic. Steel slag is highly resistant to factors that cause deterioration of ballast including extremely large cyclic loadings, vibrations of varying frequencies and intensities, repeated wetting and drying involving crystallization of rain-dissolved soluble salts, and freezing and thawing in cold climates.

Stability

The rough-surfaced, angular particles of slag ballast that develop high internal friction are desirable to grip railroad ties, maintain proper anchorage and alignment, and provide uniform load distribution. Steel slag has a high angle of internal friction, usually in the range of 45–50 degree. The hardness of steel slag on the Mohs scale is usually

6–7, compared to values of 3–4 for limestone and 7 for quartz. Change in gradation under traffic is negligible due to the hardness and high stability, which minimizes interparticle movement. Its heavy weight provides a high resistance to lateral movement on curves and washout protection in areas subject to flooding.

Electrical resistance

Railroad ballasts should have a high electrical resistance in wet and dry conditions so as not to interfere with track circuits used with signal systems and grade crossing warning systems. A minimum resistance of 2 Ω per thousand feet of track is required. The average electrical resistance of steel slag on rainy day is 160 Ω. This resistance value is far in excess of the minimum specified to avoid affecting track circuits. Research results of these tests show that there is no influence on signal transmission when steel slag is used for railway ballast (Merkel, 2007).

8.3.2.2 Installation methods

Standard construction equipment and practices are used for installing ballast material. Placement and compaction of subballast and the lower part of the ballast can be done with regular ballast placing and tamping procedure or with roadway and embankment construction equipment. Placement and tamping of the top ballast around and between ties in the final track alignment may be done either with hand tools on a small job or with special ballast placing and tamping machines used by the railroads on larger projects.

8.3.2.3 Cost

Steel slag ballast prices vary somewhat in different project areas, but are comparable to those of other types of aggregates at the plants. Overall ballast costs, of course, must include maintenance and labor (NSA, 2015). Fig. 8.7 shows steel slag ballast used in a railroad track.

Fig. 8.7 Steel slag railroad ballast.

8.3.3 Geotechnical uses

Steel slags have been successfully used to enhance the bearing capacity of difficult soils to support foundation or improve subgrade soil. Jones (2005) reported EAF slag had been used in the construction of stone column piling using the vibrofloatation ground stabilization method. EAF slag samples from the MultiServ operation in Jubail, Saudi Arabia, were examined rigorously for mechanical properties of the slag and the potential impact on the environment prior to use.

Vibrofloatation ground stabilization is a method of ground stabilization accomplished through the formation of stone columns. The creation of these stone columns is achieved by initially forming a deep vertical shaft in the ground, using a large vibrating poker with high-pressure water jets. These pokers can be inserted to 5–15 m (1.6–49 ft.) in depth. In addition to creating a hollow space in the ground, they also provide densification of the surrounding soil by high-frequency vibration of the poker. The resulting hole is filled with stone of a specific size fraction, or a combination of size fractions, and compacted using the vibrating poker. The poker itself uses either compressed air or electric motors to drive eccentric weights for the vibration mechanism. It is usually 300–400 mm (12–16 in.) in diameter and can weigh up to 4 tonnes (4.4 tons). The diameter of the final column will depend on the stiffness of the soil but can be up to 1 m (3.3 ft.).

The EAF slag used for the construction of stone columns was in the size fraction 25–75 mm (1–3 in.) (for wet applications) and 19–37 mm (3/4–1 1/2 in.) (for dry applications). The physical and mechanical properties of the EAF slag used are shown in Table 8.8.

Table 8.8 **Physical and mechanical properties of slag and limestone**

Property and test method	EAF slag	Abuhaydriah limestone	Riyadh road limestone
Bulk specific gravity ASTM C127	3.75	2.56	2.59
Water absorption (%)	0.4	1.5	1.61
Los Angeles abrasion (% loss) ASTM C131	16	35	25
Magnesium sulfate soundness loss ASTM C88	0.9	12	12
Angel of internal friction	40–50	20–35	20–35
Hardness (Mohs scale)	6–7	3–4	3–4
Aggregate impact value BS 812	11	24	20
Elongation index BS 812	10	20	18
Flakiness index BS 812	6	25	27
Clay lump and friable particles ASTM C142	0.2	0.54	0.42
Chloride content (%)	0.017	0.024	0.021
Slake durability index ISRM	99.1	N/A	N/A

Data from Jones, N. (2005). The use of steel slag aggregate for stone column ground stabilization. In: *The 4th European slag conference*, *June 20–21*, *Oulu*, *Finland*.

The EAF slag aggregate satisfies the requirements of shape, durability, strength, interlock, and resistance to abrasion and more importantly, is far superior to the alternate natural aggregate that is economically available.

As the steel slag aggregate is placed below the water table, chemical analyses relating to mechanical stability and potential environmental pollution were undertaken. Results of the tests proved positive and the slag was passed as an acceptable material for this application. It was concluded that (i) the slag could be placed in the local soil and groundwater without any environmental risk; (ii) the pH value was high due to high calcium content in the raw glassy (silicate) slag, but because of the permanent silicate bond of the calcium and magnesia, these chemicals are only marginally soluble in water; and (iii) the free lime was at a very low level (0.28%), indicating no swelling potential for the material. EAF slag demonstrated superior performance over locally available alternate natural aggregates in terms of crushing strength, water absorption, internal friction, and durability. In relation to the chemical suitability of the slag in terms of both volume stability and leachability, the slag has proven to be totally acceptable for stone column construction.

Yzenas (2010) reported that a research and implementation work has been conducted in Indiana using steel slag to enhance soil stability for highway construction.

8.3.3.1 Research

An EAF slag from Edw C. Levy Co. was used that was of a 0–12.5 mm size. The engineering properties were characterized including specific gravity, chemical analysis, optimum moisture content, MDD, and unconfined compressive strength. Expansion tests were also performed to assess volumetric stability, and total metals and toxicity characteristic leachate procedures (TCLPs, SW-846) were performed to determine environmental acceptability. Volumetric expansion tests were conducted and extended to 210 and 270 days. The expansion on the slag continued to increase throughout the 270-day test period. The aging did have an effect by reducing the level of expansion by 20–25%, but not to a level that was considered acceptable for this application. Then Class "C" fly ash was added at 5%, 10%, and 20% to the EAF slag to remediate the swelling and act as an activator for the slag. The fly ash was successful in remediating the instability. At 210 days the expansion had flatlined at ~98% below the untreated materials and at a level acceptable for geotechnical applications. The TCLP was performed to verify the acceptability of this material. The EAF slag was well below the local and federal limits for both of these procedures. The unconfined compression results of straight EAF slag showed no significant strength gains over time. However, the effect of the Class "C" fly ash on the mixtures showed significant strength gains with time. These values were higher than those typically achieved in local soils. The addition of 5% Class "C" fly ash also stabilized the swelling to negligible levels, while levels at 10% and 20% suppressed the swelling completely. Based upon the results of the expansion test, unconfined compression test, and TCLPs it was determined that the EAF slag + 10% Class "C" Fly Ash was an acceptable starting point for implementation.

8.3.3.2 Implementation

The state of Indiana requires that a 345 kPa (50 psi) strength gain, over the strength of the virgin soil being utilized, be attained within 1 day to qualify for soil stabilization. The strength gains achieved at 1 day easily exceeded that requirement (282 kPa + 345 kPa = 627 kPa). The material was mixed into the existing soil, at optimum moisture, and then compacted to 90% of Proctor prior to paving. To date the implementation has been successful on this project with additional projects being planned and constructed. As the project has progressed the product has also been evolving into a steel furnace slag soil cement (Yzenas, 2010).

8.3.4 Other uses

8.3.4.1 Railway track base

Research has been carried out for the use of steel slag as a base course material in railway track construction. The railway track structure is somewhat similar to highway pavement structure. However, in railway track the base courses is formally considered part of the earthworks, whereas the base course in roadways is a component of the pavement. In addition, very high speed and significant dynamic loads have to be taken into account in railway design and construction.

The test line is a transfer track between Salzgitter AG and Volkswagen AG in the area of a freight center, where the 240 m length of the base course was built with a mix of BOF slag and natural sand. The adjacent areas were laid in limestone and natural sand. The research conclusion was that the use of EAF slag does not influence the signaling system operation. The ballasted track consisting of EAF slag, as examined at the measurement site, is hence suitable for this signaling system operation and is approved. Steel slag has been accepted as their standards in Germany as base material for railway track construction (Merkel, 2007).

8.3.4.2 Marine use of carbonated steel slag

JFE Steel Corporation developed technology to solidify steel slag by casting it in a mold and blowing CO_2 gas, which is generated in the same steelworks, into slag, and commercialized the solidified slag as a reef material for constructing algae beds under the trade name Marine Block. Since Marine Block is manufactured by turning f-CaO in steel slag into stable $CaCO_3$ using CO_2 gas, it is free from expansion or pH problems. JFE Steel combined Marine Block with granulated blast furnace slag (GBFS) and steel slag to form models for constructing algae beds and shoals, and tested them at several areas in Japan. Through the tests, the models proved excellent for algae beds and effective in newly forming colonies of marine life (Nakagawa, 2007).

8.4 Research and development

8.4.1 Criteria establishment

For steel slag use as an unbound granular material in unconfined applications such as granular base, volume expansion (stability) is of major concern. A usability criterion for unconfined applications has been developed based on the physical properties of a given slag:

$$F \leq k\frac{\left(\gamma_s - \gamma_o\right)}{\gamma_s^2} \times 100\% \tag{8.2}$$

where F is the hydratable oxide content (CaO and/or MgO) of a given slag; γ_s is the specific gravity of the slag; γ_o is the bulk relative density of the slag; and k is a constant related to the slag's physical properties. When the hydratable oxide content of a given steel slag is less than the right-hand term, the slag will not expand macroscopically when used as a granular material. This must then be confirmed through standard slag expansivity testing (refer to Chapter 9).

8.4.2 Mixing use with other by-products

Research has been conducted by different researchers to explore mixing the use of steel slag with other materials to lower the volume expansion rate.

Using 70–85% of weathered BOF slag with 15–30% of GBFS, a road base was constructed without expansion damage. BOF slag aggregate and ACBFS were mixed as well for road base construction, which led to mixtures of acceptable volume stability (Deneele, de Larrard, Rayssac, & Reynard, 2005).

Domas and Reynard (2010) tested different steel slag and BF slag combinations to assess the environmental behavior of slag used in road applications, including aggregates for embankment and pavements. Mechanical and geotechnical characterization of the combined samples was conducted first in a laboratory to check the suitability of these slags to be used in proposed applications, followed by field implementation including slags in road base applications (aggregates for embankment, road layer, and technical platform for industrial site). Test results made the materials fully adapted for uses in road base applications. The leaching test results showed most of the samples had the same release levels on the same order as for inert materials.

8.4.2.1 Mixture of steel slag and dredged clay

The Japan Iron Steel Federation has developed technology to use steel slag for constructing shoals and backfilling of sunken sea beds after mixing it with soft dredged clay arising from digging of ship lanes. This technical development envisions effective use of the solidifying properties of steel slag and its water-purifying properties to adsorb phosphorus and hydrogen sulfide in sea-bottom sediment that causes red and blue tides, respectively, to contribute to the improvement of the marine environment (Nakagawa, 2007).

8.5 Summary

Research and construction practice have proved that air-cooled slag can provide a high level of performance in unbound uses. The good performance and slag aggregate products emanate from well-controlled production processes with good quality control procedures.

Although it has been proven that laboratory study and field trials with rigorous property characterization will generate good materials and end products without adversely affecting the surrounding environment, there are still urgent needs for the development of novel uses of various slags in unbound materials so that large quantities of slag can be consumed. Research and field trials are critical for new specification establishment and update and revision of the existing specification to making them reflect current engineering reality.

A purely technological approach is insufficient for developing new slag end uses and products. New utilization can only be realized based on scientific and technological research. Scientific knowledge allows understanding or formulating hypotheses on the base of a distinct material behavior. The process requires the involvement of specialists who know the technology, policy, and regulations, and market to be explored. Collaborations of researchers, slag producers and processors, government agencies, environment regulators, and contractors can create good results for the novel use of slag. Guidelines, quality control, and compliance rules for order acceptance and delivery of slag products are critical for the practical use of slag foundation and geotechnical work.

Questions

8.1 What is the difference between a natural aggregate and a manufactured aggregate?

8.2 Aggregates may be classified as fine aggregate or coarse aggregate; explain the difference.

8.3 How does particle shape affect the use of aggregate in base course materials?

8.4 Explain the use of Fuller's maximum density curve.

8.5 Review the ASTM specifications for tests concerning the general quality of aggregates, deleterious materials in aggregates, and the specifications used in the design of Portland cement and bituminous concrete mixes, and write a short report on the purposes, procedures, and reasons for the tests.

8.6 Why can blending use of slag and other materials lower steel slag expansion?

8.7 How is slag evaluated prior to use as a unbound granular?

8.8 To be used as unbound granular, must the f-CaO content be zero?

8.9 List the physical and mechanical properties of air-cooled blast furnace slag and steel slag.

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Usability criteria for slag use as a granular material

9

9.1 Introduction

Air-cooled and crushed slag can be used as unbound granular materials in broad applications, which include pavement subbase and base aggregate, railroad ballast, port and harbor construction stone, dam and embankment construction stone, soft soil stabilization stone, engineered and foundation fill, riprap, armor and gabion stone, erosion control, and slope protection stone. Each use as a granular material must be technically proven. For steel slag and some nonferrous slags containing free lime and periclase, volumetric stability is one of the importance factors to be checked. As indicated in Chapter 6, one of the prohibiting factors of using slag in civil infrastructure construction on the technical side is the lack of technical guidance and usability criteria pertinent to different applications. For example, for slag use as a granular material in road base courses, one of the criteria currently used is the free lime content, which comes from empirical data. One free lime limit may not be related to all different uses.

It is critical to establish quantified properties and criteria to guide the extensive use of slags and remove the main inhibiting factor contributing to low utilization rate. Pertinent specifications and quality requirements supported by the criteria can guide rational and sustainable use of slag. It is essential to inclusively understand the compositional and physical properties of slag, the conventional materials, end products, and final uses in which slag is involved.

From Chapter 6, it is possible to establish quantitative relationships between slag and various end products: for example, for slag use in nonrestrained conditions, restrained conditions, or rigid matrixes, and cement manufacture. The control parameters are different in different applications.

As is known, restrictions on slag aggregate use as a granular material come mainly from two aspects: the variation of volume stability of slag due to volume expansion of slag particles, and the lack of criteria developed to date to prove the relation between the expansion property of slag and the stability of unbound applications. Note that, however, some steel slag does exist that is sufficiently stable to be used in cement concrete without making the concrete disrupt, even under rigorous treating conditions. The criterion for this utilization will be discussed in Chapter 12.

For slag, typically steel slag, the following questions can be raised:

1. What is the mechanism of volume expansion, chemically and physically?
2. What is the theoretical resultant volume expansion due to free lime or periclase particles in steel slag and other slags?
3. How different is the disrupture model of bulk unbound use from slag use in hot-mix asphalt (HMA) or cement concrete?

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4. Can the void volume in a bulk use absorb the increased volume “internally” and make no apparent volume expansion?
5. Is the answer to Question 4 is yes, what is the condition, or under what external force, can this happen?

These questions will be answered in the sections below.

9.2 Quantification for use in nonrestrained conditions

From Chapter 8 it was found that slag can be used in broad areas of construction applications; for example, use in blended cement manufacturing, use as a granular material in road base or subbase courses, and use as an aggregate in various asphalt mixes, pavement surfaces, and concrete.

One of the prohibiting factors is lack of technical guidance and usability criteria pertinent to different applications.

In this section, steel slag is used as the objective slag due to its typical expansive nature. Other nonferrous and nonmetallurgical slags may have an expansive nature due to unhydrated lime and/or periclase contents. Particularly, the examples of slag use in nonrestrained conditions as unbound granular base and restrained condition as an aggregate in concrete are used. However, the methodology can be referred to other slags having expansion natures or containing unhydrated lime or periclase.

The overall use of blast furnace slag, which is from ironmaking, is relatively well known for a range of construction applications from granular base, concrete. or HMA aggregate to supplementary cementitious materials. In contrast to blast furnace slag, which is volumetrically stable and straightforward in its construction uses, steel slag from a basic oxygen furnace (BOF) and an electric arc furnace contains free (unhydrated) lime (f-CaO) that can result in volumetric instability (expansion) that must be dealt with through appropriate steel slag aging, testing, and quality control to ensure its appropriate use in construction. Each specific slag, in terms of type, process, and source, should be fully evaluated for each proposed use, given the significant differences in properties that can be involved and the specific performance requirements for bulk uses.

Although there are advantages in each application, the use of steel slag as a granular material is a promising area for the following reasons: (i) larger quantities of steel slag can be used as a granular material in unbound conditions, such as road base or subbase, compared with other uses; (ii) the process for granular use is technically mature and sound, simpler, and well developed; (iii) there is less concern on long-term stability in unbound conditions, highway granular base, and subbase, for instance; (iv) the volume expansion test method has also been developed (ASTM, 2006); and (v) the steel slag processing industry has maturely placed their production and marketing emphasis on granular materials and aggregate for unconfined utilizations. Steel slag treating and processing technology has been well developed for the last couple of decades, which has made it possible for steel slag to be used as granular base or subbase materials in highway construction at a large scale (Shen, Zhou, Ma, Hu, & Cai, 2009;

Wang & Emery, 2004; US EPA, 2010). However, the fact is that steel slag aggregate has not been extensively used in construction, especially its use as a granular material. In 2000, approximately 13 mt of steel slag was discharged in the United States, but only 1.7 mt was used in construction in 2000 (USGS, 2010). The main reason for the low-scale utilization is the lack of quantified criteria to guide the appropriate use for a special steel slag in a special use. It is imperative to establish different criteria for different utilizations of steel slag.

Different applications should have different criteria to guide appropriate use. For example, for the use of steel slag in concrete or other rigid matrices, expansion force of steel slag and the distribution of the force in the rigid matrices governs usability (Wang, 2010). There is no single criterion governing different uses of steel slag. When steel slag is used as a granular material (eg, road base or subbase), the apparent volume expansion of the base or subbase is to be restricted to zero. However, a bulk granular material contains void content even it is fully compacted (the maximum compaction value of the laboratory Proctor value). Can the void content in the compacted bulk slag aggregate absorb any volumetric expansion generated by the expansive steel slag? To answer this question, the following work must be conducted: (i) determine the theoretical volume expansion rate of steel slag, which can be determined based on the chemical reactions incurred in the slag samples when reacting with moisture; (ii) perform laboratory volume expansion testing with and without surcharges (ie, the weight surrounding the sample three dimensionally); and (iii) establish the relationship between free lime content and theoretical expansion under constraint force, and furthermore, develop the usability criteria. The criteria should be based on the relationship between the estimated volume expansion equation (in percentage, derived from chemical and physical changes of free lime in steel slag) and the minimum percentage of void volume that can take the expansion of steel slag under certain external weight (surcharge).

9.2.1 Basic properties of steel slag and expansion mechanism

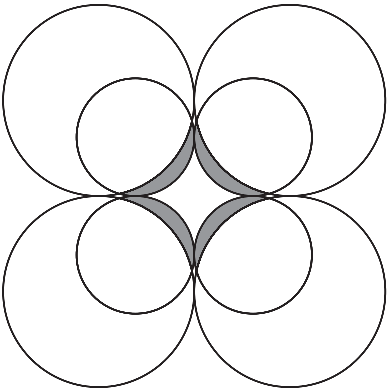
9.2.1.1 Chemical and mineral compositions

Solid steel slag exhibits a block, honeycomb shape and high porosity. Most steel slag consists primarily of CaO, MgO, SiO_2, and FeO. In low-phosphorus steelmaking practice, the total concentration of these oxides in liquid slags is in the range of 88–92%. Therefore, the steel slag can be simply represented by a CaO-MgO-SiO_2-FeO quaternary system. However, the proportions of these oxides and the concentration of other minor components are highly variable and change from batch to batch (even in one plant) depending on raw materials, type of steel made, furnace conditions, and so forth.

Steel slag can be air-cooled or water quenched. Most of the steel slag production for granular materials use natural air-cooling process following magnetic separation, crushing, and screening. Air-cooled steel slag may consist of big lumps and some powder. The mineral composition of cooled steel slag varies and is related to the forming process and chemical composition. Air-cooled steel slag is composed of $2CaO \cdot SiO_2$, $3CaO \cdot SiO_2$ and mixed crystals of MgO, FeO, and MnO (ie, $MgO \cdot MnO \cdot FeO$), which can be expressed as RO phase. CaO can also enter the RO phase. In addition, $2CaO\text{-}Fe_2O_3$, $CaO \cdot Fe_2O_3$, $CaO \cdot RO \cdot SiO_2$, $3CaO \cdot RO \cdot 2SiO_2$, $7CaO \cdot P_2O_3 \cdot 2SiO_2$, and some other oxides exist in steel slag (Sersale, Amicarelli, Frigione et al., 1986; Shi, 2004). It was reported that the X-ray diffraction pattern of steel slag is close to that of Portland cement clinker.

9.2.1.2 Expansion mechanism

During the steelmaking process, fluxes that consist of lime (CaO) or dolomitic lime, with iron and scraps, are charged to the furnace. There is a certain amount of free lime (f-CaO) in steel slag. Free lime, with a specific gravity of 3.34, can react with water to produce $Ca(OH)_2$, with a specific gravity of 2.23, which results in volume increase (Fig. 9.1). This is considered to be the primary reason to make steel slag expand volumetrically (Montgomery and Wang, 1993).



Small spheres: initial volume of solid phase
Large spheres: final volume of solid phase
Space between small spheres: initial volume of void
Hatched areas: increment of void
Space between large spheres including hatched areas: final volume of void

Fig. 9.1 Effect of increase of solid phase on the void volume.

MgO in steel slag is in the form of wüstite (ie, Fe (Mn, Mg, Ca)O), in glassy state, mixed crystal or solid solution mainly with FeO and MnO (ie, RO phase). The free form of MgO (periclase) is volumetric unstable, which can only be formed in low-basicity condition. Due to the high-basicity condition in molten steel slag and the close radii of Mg^{++}, Fe^{++}, and Mn^{++} (0.78, 0.83, and 0.91Å, respectively), MgO, FeO, and MnO usually form solid solution. In this study, free lime is considered to be the major contributor to the volume expansion of steel slag. The expansion mechanism of free MgO (periclase) can be explained similarly using the diagram in Fig. 9.1.

9.2.2 Theoretical volume expansion

As depicted in Fig. 9.1, the volume change of free lime due to its hydration includes two parts—chemical and physical—that can be calculated. However, the physical portion of volume change has been neglected. In the following deduction, volume changes due to both chemical and physical changes are considered.

9.2.2.1 Hydration of free lime and volume change

The hydration speed of free lime in steel slag is relatively slow compared with that of burnt lime in which the hydration can be completed within approximately 30 min (Thomson, 2005). This is because the structure of free lime in steel slag is denser due to the calcining temperature of approximately 1700 °C (3092 °F) and the decreased ability for moisture to react with free lime.

The reaction of free lime and water can be expressed in Eq. (9.1):

$$\mathrm{CaO} + \mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2} \pm 15.5\,\mathrm{Cal/Mol} \tag{9.1}$$

Under ambient temperature, the reaction proceeds to the right-hand side. The reaction proceeds to the left-hand side only at 547 °C (1017 °F) or above (Lea, 2004).

The volume change, due to chemical reaction, of a lime–water system and solid phase (lime) can be calculated as presented in Table 9.1. From Table 9.1, the absolute volume of the solid phase increases by 97.92%. However, in the free lime–water system, the total volume does not increase; instead, it decreases by 4.54%. The chemical reduction occurs when lime reacts with water, which is the same as for other cementitious materials such as Portland cement and gypsum.

9.2.2.2 Volume expansion due to physical change

The void volume of free lime particles can be explained according to Fig. 9.1. When hydration occurs, the void volume increases in conjunction with the increase of the solid phase. Because the free lime particle size is adequately tiny, it is assumed here that the particles of free lime are spherical before and after hydration and are fully compacted in ideal hexagonal form. Under these conditions, the volume of solids is 74% of the total volume and the void volume accounts for 26% of the total volume. The relative contents or the ratio of solid to void are constant and are not related to the particle size. However, the absolute value of the void volume is variable with the change of solid phase.

In Fig. 9.1, if the surfaces of the small spheres absorb other substances (during the process of hydration, lime particles absorb water molecules, thereby increasing the solid phase volume), small spheres will become large spheres although the ratio of spheres (solid) to void does not change and the absolute volume increases. This means that if the volume of spheres increases by 1%, the void volume will increase by $26/74 \times 1\% = 0.351\%$. As said in the above deduction, very fine particles of free lime (normally ~ 100 μm) are assumed to be a spherical shape. Because of the tiny particle size and also that the volume change caused by physical shape change contributes only

Table 9.1 Volume change of free lime–water system

Equation of reaction	Molecular weight	Specific gravity	Absolute volume of the system (cm^3)		Absolute volume of the void phase (cm^3)		Absolute volume change (%)	
			Before reaction	After reaction	Before reaction	After reaction	System	Solid phase
CaO +	56.08	3.34						
H_2O	18.02	1.00						
=								
$Ca(OH)_2$	74.10	2.23	34.81	33.23	16.79	33.23	−4.54	97.92
Water needed for the reaction	0.321							

approximately 25% of the total volume change, it is considered to be acceptable in the estimated volume expansion equation deduction.

From Table 9.1, for complete reaction, the solid phase will increase by 97.92%. Therefore, the void volume will increase by 26/74 × 97.92% = 34.40%.

When free lime hydrates, the increase in solid phase results in increase of void volume. The combined increase of solid phase and void will surpass the volume change of the free lime–water system resulting in an increase in lime volume. The increase will be 34.40% + 97.92% = 132.32%. The expansion of the solid phase is larger than that of the free lime–water system. Therefore, the actual volume expansion of free lime in steel slag after complete reaction is 132.32 – 4.54% = 127.78%.

9.2.2.3 An equation for prediction of steel slag volume expansion

From the expansion mechanism of free lime, an equation for estimating the potential volume expansion of steel slag can be deduced.

A bulk steel slag aggregate sample is considered. The apparent total volume is V_o, the volume of solid is V, and the ratio V/V_o (or γ_o/γ_s) is a measure of the denseness of the mass of steel slag (expressed as D). The volume expansion is defined as the ratio of increase in volume to the real volume (solid) of steel slag; that is,

$$E_s = \Delta V / V \tag{9.2}$$

where ΔV is the volume increase of steel slag. As indicated, the increase in volume of the steel slag is entirely due to increase in volume of free lime in the steel slag (periclase can be considered separately). The mass of the steel slag is $V\gamma_s$, the mass of the free lime is $V\gamma_s F$ and the volume of free lime in the steel slag is $V\gamma_s F/\gamma_l$. Therefore, the volume expansion, E_s, of the steel slag can be expressed as:

$$E_s = \frac{1}{V_o D} \times \frac{V_o D \gamma_s F}{\gamma_l} \times \frac{E_l}{100} \tag{9.3}$$

where E_l is the volume expansion of lime (%) and equals 127.78% as calculated above; E_s is the volume expansion of steel slag, (%); V_o is the apparent total volume of steel slag, (cm^3); D is the denseness of steel slag (γ_o/γ_s); F is the free lime content of the steel slag (%); γ_o is the bulk density of steel slag samples with voids (g/cm^3); γ_s is the specific gravity of steel slag (g/cm^3); and γ_l is the compacted density of lime (g/cm^3)

Substitute $\gamma_l = 3.34$ and $E_l = 127.78\%$ into Eq. (9.3),

$$E_s = 0.38 \times \gamma_s F \tag{9.4}$$

From Eq. 9.4, it can be seen that the volume expansion of steel slag is related to the compacted density, γ_s, and the free lime content of the steel slag, F. However, γ_s is a constant for a particular slag (g/cm^3). Therefore, the volume expansion is directly related to the free lime content. It is noted that 0.38 has a unit reversing to the unit of $\gamma_{s.}$

9.2.3 Laboratory volume expansion testing

9.2.3.1 Test method and equipment employed

In the deduction of Eq. (9.4), the real volume V (ie, $V_o D$), was considered. However, when steel slag is used as a granular material in unrestrained conditions such as road base or subbase, it must be treated as an entirety. Internally, the void content is normally not zero, or in other words, the denseness, D, is not 100%. To verify if the void volume in a bulk steel slag sample can absorb volume expansion "internally," and to verify the expansion prediction equation, volume expansion tests need to be conducted on slag samples with and without surcharges.

The American Society for Testing and Materials (ASTM) standard test method (ASTM, 2006) was adopted in the laboratory testing. The diameter of the testing mold is 15.24 cm, the area is 182.4 cm^2, and the height of the section containing materials is 12.8 cm. Steel slag samples were tested in the mold under conditions with and without 4,560 g (25 g/cm^2) surcharges. The slag samples were soaked in water bath at 74 ± 3 °C. Figs. 9.2 and 9.3 give the view of the volume expansion testing.

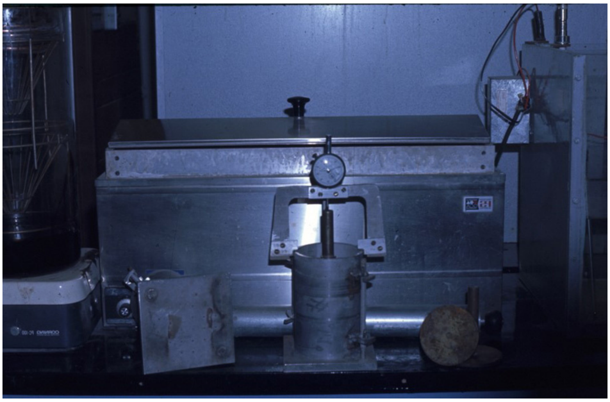


Fig. 9.2 View of the volume expansion test equipment according to ASTM D4792.

Fig. 9.3 Parallel volume expansion test.

Samples were initially selected for the expansion test to qualitatively verify if any differences of volume expansion exist. Two parallel tests, with and without surcharges, for each sample with nominal particle size of 20 mm (16–20 mm) were carried out.

9.2.3.2 Test results

Three samples were initially selected (ie, BOF slag 1, BOF slag 2, and BOF slag 3), which are air-cooled BOF slags from different sources. The properties of the three slag samples and the estimated volume expansion are presented in Table 9.2.

Table 9.2 Properties of steel slag samples for the comparison of the volume expansion test

	BOS slag 1	BOS slag 2	BOS slag 3
Free lime content (f-CaO, %)	1.84	0.34	1.27
Specific gravity of slag sample (γ_s, g/cm^3)	2.98	3.08	3.16
Estimated volume expansion based on Eq. 6.4	2.08	0.39	1.52

The volume expansion test results with and without surcharges are shown in Table 9.3.

From the results in Tables 9.2 and 9.3, it can be seen that (i) differences do exist between the surcharged and nonsurcharged samples; (ii) the differences, or differentials, K_{25}, which means under 25 g/cm^2 surcharge, are from 7% to 13%; (iii) the lower limits happened when the expansion rate became stable (ie, in the later testing days); and (iv) the estimated Eq. (9.4) is fairly reliable for estimating the major expansion, which occurs during the first 1–2 weeks of hydration. Fig. 9.4 presents the expansion test results of the three BOF slag samples with and without surcharge (7–13% differences).

The differences caused by the 25 g/cm^2 surcharge are important to set up the usability criterion. Yet, the lower limits of the differences should be used in the usability criterion as it will place the criterion on the safe side.

To further quantitatively verify the lower differentials, six steel slag samples with 20 mm nominal size (16–20 mm) were selected to run 12 parallel tests with and without surcharges. The densities and free lime contents of the steel slag samples are shown in Table 9.4. American Association of State Highway and Transportation Officials (AASHTO) T 85 Testing Method–Specific Gravity and Absorption of Coarse Aggregate were used for determination of γ_o and γ_s. The volumetric analysis method was used in determination of free lime content. The lower limits of differentials after the volume expansion become stable are shown in Table 9.5.

Results have shown that the maximum expansion value ranged from 0.56% to 2.55% (Table 9.4). Comparing two parallel tests of each sample, it was found that expansion values of the slag samples with surcharge are lower by 7.7% to 10.9%, on average, than those of the samples without surcharges. This difference is called differential in expansion and expressed as K_{25}.

Table 9.3 Volume expansion test results

	BOF slag 1			BOF slag 2			BOF slag 3		
	Volume expansion (%)		*Differential in expansion (%, K_{25})*	Volume expansion (%)		*Differential in expansion (%, K_{25})*	Volume expansion (%)		*Differential in expansion (%, K_{25})*
Testing days	*Surcharge*	*Nonsurcharge*		*Surcharge*	*Nonsurcharge*		*Surcharge*	*Nonsurcharge*	
1	0.15	0.17	13.0	0.17	0.19	11.2	0.12	0.14	16.6
2	0.36	0.40	11.1	0.27	0.30	11.1	0.23	0.26	13.0
3	0.54	0.61	13.0	0.34	0.37	8.8	0.32	0.36	12.5
4	0.69	0.77	12.0	0.37	0.40	8.1	0.41	0.45	9.8
5	0.86	0.95	10.0	0.40	0.43	7.5	0.50	0.55	10.0
6	1.00	1.12	12.0	0.42	0.45	7.1	0.59	0.65	10.2
7	1.13	1.26	11.5	0.43	0.46	7.0	0.70	0.76	8.6
8	1.35	1.49	10.4				0.81	0.89	9.9
9	1.48	1.64	10.8				0.98	1.10	12.2
10	1.59	1.73	8.8				1.17	1.26	7.7
11	1.71	1.83	7.0				1.24	1.36	9.7
12	1.85	2.01	8.6				1.30	1.41	8.5
13	1.95	2.13	9.0				1.36	1.47	11.0
14	1.96	2.14	8.0				1.41	1.53	8.5
15							1.42	1.54	8.5
16							1.44	1.55	7.6

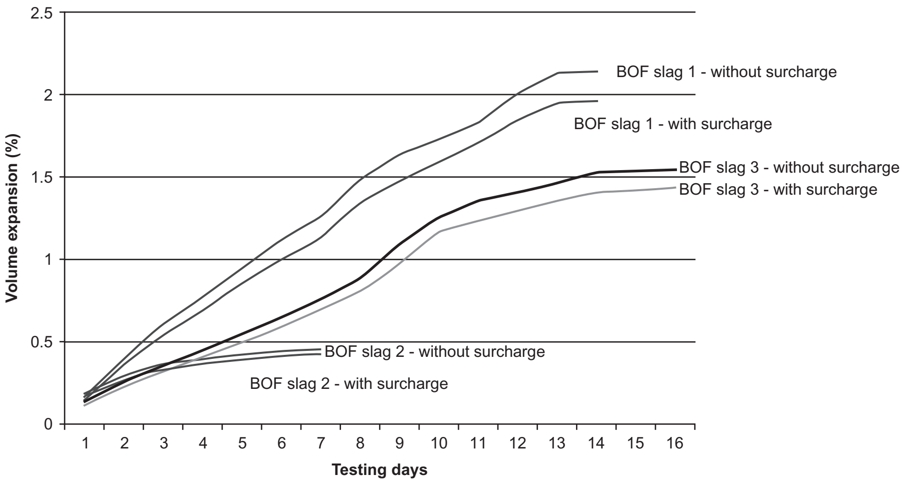


Fig. 9.4 Volume expansion results for three BOF slags with and without surcharge.

Table 9.4 Densities and free lime content of steel slag samples

Sample number	BOF 2-1	BOF 2-2	BOF 2-3	BOF 2-4	BOF 2-5	BOF 2-6
γ_o	2.35	2.28	2.149	2.31	2.19	2.24
γ_s	3.36	3.27	2.89	3.19	2.99	3.26
F (%)	2.7	3.5	3.3	3.1	2.4	3.4

Table 9.5 Volume expansion results of six BOF slags

Samples	Surcharge	Nonsurcharge	Differential in expansion (%, K_{25})
BOF 2-1	1.85	2.01	8.6
BOF 2-2	2.30	2.55	10.9
BOF 2-3	0.56	0.62	10.7
BOF 2-4	1.35	1.49	10.4
BOF 2-5	1.95	2.10	7.7
BOF 2-6	1.96	2.16	10.2

9.3 The development of usability criteria for nonrestrained use

9.3.1 Usability criteria for the use of steel slag as granular material

From the volume expansion tests, it can be seen the lowest differentials caused by the surcharge are 7–8%. That means if the estimated expansion, Eq. (9.4), is less than 7–8% of an estimated voids content (7.5% is taken below) and the material is acted upon by a 25 g/cm^2 surcharge, actual expansion volume of the steel slag will not occur. In other words, if

$$E_s < 7.5\%(1-D) \tag{9.5}$$

or

$$0.38 \times \gamma_s F < 7.5\%(1-\gamma_o/\gamma_s)(25\text{g/cm}^2\text{surcharge}) \tag{9.6}$$

apparent volume expansion of the granular material will not occur. In Eq. (9.5) the unit of the left side is volume change (%) and the unit of the right side is percentage of volume that can take the expansion of slag. Eq. (9.6) can be rewritten in the form

$$F < \frac{0.075(\gamma_s - \gamma_0)}{0.38\gamma_s^2} \times 100\% \tag{9.7}$$

It states if free lime content in the steel slag is less than the right-hand term, the steel slag will not expand macroscopically, or the expansion resulting from free lime can be "absorbed" by the void volume of steel slag itself under a pressure of 25 g/cm^2. In other words, overall expansion will not occur if this condition is met. It simply provides a convenient estimation for a given steel slag with a known content of free lime content and physical properties. Eq. (9.7) has been developed experimentally for steel slag under the condition that the steel slag material exerted a pressure 25 g/cm^2 above in the pavement structure. Fig. 9.5 shows asphalt pavement structure layers, which include HMA layers, normally 100–300 mm (4–12 in.) thick; granular base and subbase layers. Fig. 9.6 provides a view of the granular base and/or subbase layers under the "surcharge" of HMA layers. It is assumed that the thickness is larger than 100 mm (4 in.) and the surcharge is larger than 25 g/cm^2 condition.

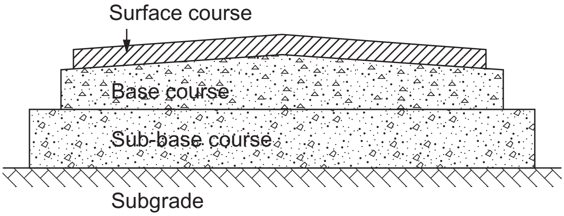


Fig. 9.5 View of pavement structure.

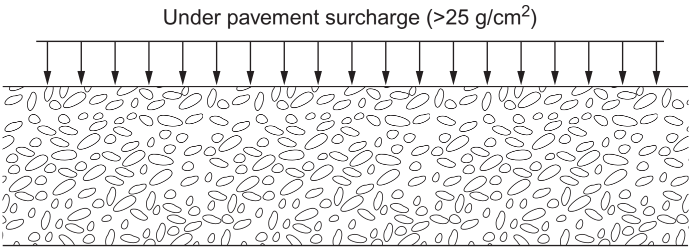


Fig. 9.6 Slag aggregate as a base or subbase in the pavement structure with the surface course generally thicker than 10 cm (4 in.), meeting the condition by the criterion.

9.3.2 Modification of the criterion

The literature has reported that the measured free lime content comes from two sources: residual free lime and precipitated lime from the molten steel slag (Sersale, Amicarelli, Frigione et al., 1986). The volume expansion of steel slag is contributed by the content of residual free lime. When the measured total free lime is less than 4%, it contains 2% precipitated lime; if the measured total free lime is larger than 4%, it contains 2.8% precipitated lime (Geiseler, 1996). Thus, the final modified criterion can be rewritten as follows in two parts:

When measured free lime is ≤ 4%, the allowable free lime content is

$$F_{all} < 2.0\% + \frac{K_{25}\left(\gamma_s - \gamma_o\right)}{0.38\gamma_s^2} \times 100\% \tag{9.8}$$

When measured free lime is > 4%, the allowable free lime content is

$$F_{all} < 2.8\% + \frac{K_{25}\left(\gamma_s - \gamma_o\right)}{0.38\gamma_s^2} \times 100\% \tag{9.9}$$

where F_{all} is the allowable (or maximum) free lime content for a given steel slag that is evaluated for possible use as a granular material with a condition that above the steel slag there is a structure layer(s) thicker than 10 cm upper layer(s), or a surcharge larger than 25 g/cm^2 within the pavement structure.

9.3.3 Discussion

The testing equipment with surcharge is considered to be a simulation of road base or subbase granular materials. The 25 g/cm^2 surcharge is equivalent to a minimum 10 cm thick (4 in.) concrete or HMA pavement on top of steel slag granular base course on subbase course. From the test results of the six samples, it is calculated that the allowable free lime contents for the samples to be safely used as a granular base or subbase is in the range of 3.7–3.9%, under the condition of 25 g/cm^2 constraint force; that is, 10 cm thick upper layer of pavement structure.

The literature provides the free lime limits for steel slag use as a granular material to date. Some data based on road construction suggested the limit should be about 4% (Shi, 2004; Wang & Lin, 1983). Others have suggested the limit of 4% can be extended (FHWA, 2010; Piret, 1977). However, it is noted that (i) the recommendation came from field visual observation only, and the suggested limits are for asphalt concrete aggregate, granular materials, or cementitious material applications. The criteria developed can be used for steel slag, or other nonferrous slag, producers or users to evaluate the potential usability of their products in infrastructure construction.

The ultimate maximum volume expansion of steel slag can be estimated and predicted by the theoretical expansion equation. The calculation of volume expansion based on free lime is convenient and reliable for use to evaluate the usability of steel slag. The calculated volume expansion can also be used as quality control measures during slag processing or evaluation criterion for a given slag proposed for engineering applications.

The differences of volume expansion exist due to the porous nature of granular material and the external constraint force. In other words, a certain percentage of the volume expansion takes up the void volume and makes the entire bulk steel slag sample not show apparent expansion. The lowest difference, which is most meaningful for the development of usability criteria, happened in the later hydration days, which at approximately 7%, is not related to the free lime content. For steel slag, and other nonferrous volume expansion-prone slags, when used as unbound granular material, apparent volume expansion should be taken into consideration. For the use of steel slag as an aggregate in rigid matrix (eg, Portland cement concrete), expansion force, rather than volume expansion rate should be used in the development of the usability criterion.

The criteria developed can be used as guidance for the use of steel slag as a granular material. It can also be used for other nonferrous slags. For nonferrous slags, or slags with different physical properties, it is important to conduct a laboratory testing to identify the volume expansion differentials (ie, K_{25}) that may need to substitute the factor in Eqs. (9.8) and (9.9), before using the criteria.

In most cases, the volume expansion rate of steel slag granular base materials is smaller than the void content. This is partially because of the porosity and honeycomb-shaped surfaced property. Further work should be done to find the relationships between various physical characteristics of slag aggregate and the volume differentials, or the differentials based on different surcharges.

9.4 Summary

Laboratory volume expansion testing conducted with comparison of the results of theoretical volume expansion proved that they correlated well. Furthermore, it has been experimentally proved that certain volume expansion of steel slag can be absorbed internally by the void volume in bulk steel slag under external surcharge weight making the apparent volume expansion equal zero. The minimum (lowest) absorbable void volume is approximately 7.5%, which is unrelated to the free lime content. The usability criterion is developed based on the volume expansion of steel slag (%) and the minimum percentage of the volume that can take the volume expansion of steel slag (%). Eventually the criterion (relationship) is established based on the free lime content, the specific gravity, and bulk relative gravity of a specific steel slag sample. The criteria is potential to be used as guidance and prediction for the use of steel slag and other expansion-prone nonferrous slags (eg, copper and nickel) as a granular material in highway construction.

Questions

9.1 For volume expansion-prone slag, what are the differences between the use in restrained and nonrestrained conditions?
9.2 How do the chemical and physical changes of f-CaO lead the volume expansion of steel slag?
9.3 Why can surcharges on a bulk slag aggregate absorb some volume expansion?

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Slag use in asphalt paving

10

10.1 Introduction

Hot-mix asphalt (HMA) is the predominant asphalt paving material currently used in the world. In addition to HMA, a variety of asphalt mixtures and technologies have been developed and used including stone mastic asphalt (SMA), warm-mix asphalt (WMA), cold in-place recycling (CIR), and various surface treatment techniques (chip seal, slurry seal for instance). Laboratory experiments, field trials, and construction practices have proven that quality slag aggregate can be incorporated in these asphalt mixtures by using conventional construction methods and technologies that enhance asphalt pavement performance.

The use of slag in asphalt paving is to partially or completely use slag aggregates to replace natural aggregates in asphalt mixes. Aggregates makes up approximately 92–96% of HMA and plays a very important role in highway pavement structure. The quality of aggregate directly affects the performance of the end product (ie, asphalt pavement). Asphalt concrete relies heavily on aggregate properties for stability (strength) and many other required characteristics of the mix. Research, steelmaking, and steel slag processing technology have proved steel slag can be processed into a good HMA aggregate (Dayioglu, Aydilek, & Cetin, 2014).

The ideal aggregate for an asphalt mix should have proper gradation and size, be strong and tough, and be angular in particle shape. Other properties include low porosity, surfaces that are free of dirt, rough texture, and hydrophobic nature. The aggregate gradation and size, strength, toughness, and shape are important considerations for the stability of HMA mixtures. The porosity and the surface characteristics are important to the aggregate–asphalt binder interaction. The asphalt binder must adhere to the aggregate and at the same time coat all the aggregate particles. If the aggregate particle has a low porosity and is smooth, the asphalt cement will not adhere to the aggregate. Adhesion becomes an extremely important property during periods when the mix is exposed to water. If the aggregate wets easily, the water will compete with the asphalt cement (bitumen) for adsorption onto the aggregate surface, and the aggregate will separate from the asphalt cement, which is known as slippage. The aggregate in asphalt mix, unlike that in Portland cement concrete, supplies most of the stability and thus should have a certain amount of strength and toughness; otherwise, loss of stability will result. Particle shape is a property of the aggregate that is important when it comes to asphalt mixes. When rounded aggregates, both coarse and fine aggregates, are used in an open-graded mix, very little stability is achieved. Crushed fine aggregate is critical in improving rutting resistance, which is often overlooked. Porosity of the aggregate strongly affects the economics of a mix. In each mix the aggregate should have a certain amount of porosity. In general, the higher the porosity, the more asphalt will be absorbed into the aggregate, thus requiring a higher percent of asphalt in the mix design (Derucher, Korfiatis, & Ezeldin, 1998). Depending on the specific use of

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the asphalt mix, the size and gradation of the aggregate varies tremendously. A high-quality asphalt mix for heavy traffic will generally utilize a dense graded aggregate (a well-graded aggregate from coarse to fine). Open-graded mixes are subject to greater mechanical breakdown than a dense graded mix. In any case, Fuller's maximum density curve would not be used in practice because it does not leave sufficient room for the asphalt cement. The best procedure would be to open the grading somewhat more than the maximum density. This opening of the gradation is achieved by the addition of fines (material less than the No. 200 sieve).

Slag aggregate processes many good physical and mechanical characteristics, some of which exceed the requirements of aggregates for asphalt mixes. Positive applied features of slag asphalt mixes, especially steel slag, have been proven in HMA design and construction.

Aggregate is a combination of sand, gravel, crushed stone, slag, or other mineral materials, used in combination with a binding agent to form such materials as asphalt concrete. HMA design includes the selection of the materials, aggregate and asphalt binder (asphalt cement, or bitumen), the best blend of the aggregates, and the optimum asphalt content, which provides a material that meets technical requirements economically. The major steps of HMA design includes (i) selecting materials; (ii) selecting aggregate proportions to meet the specification requirements; (iii) conducting trial mixes at a range of asphalt contents and measuring the resulting physical properties of the specimens; and (iv) analyzing the results to determine the optimum asphalt content and if the specification is met.

In the United States, the most commonly used asphalt mix design methods had been the Marshall method and the Hveem method from the 1940s to the 1990s. By 2009, almost all US states had converted over to the Superpave mix design method for highway pavement construction (NAPA, 2009). The Marshall method is still the dominant method for airfield construction projects.

The Marshall method consists of several major steps: (i) aggregates are blended in proportions that meet the specified gradation; (ii) the mixing and compacting temperatures for the asphalt cement are determined by the temperature-viscosity graph; (iii) a number of briquettes, 101.6 mm (4 in.) in diameter and 60–65 mm (2.4–2.6 in.) high, are mixed using 1200 g (2.64 lb) of aggregates and asphalt binder as various percentages both above and below the optimum asphalt content; (iv) density of the briquettes is measured to allow calculation of the voids contents; and (v) briquettes are heated to 60°F (140°F) for Marshall stability and flow measuring (Atkins, 2003; Kandhal & Koehler, 1985; Mundt, Marano, Nunes, & Adams, 2015).

Marshall stability is defined as the maximum load carried by a compacted specimen tested at 60°C (140°F) at a loading rate of 2 in./min (50.8 mm/min). This stability is generally a measure of the mass viscosity of the aggregate–asphalt cement mixture and is affected significantly by physical properties including the angle of internal frication of the aggregate and the viscosity of the asphalt cement at 60°C (140°F).

The flow is measured from the start of loading to the point at which stability begins to decrease, which is equal to the vertical deformation of the sample in hundredths of an inch or 0.25 mm. High flow values generally indicate a plastic mix that will experience permanent deformation under traffic, whereas low flow values may indicate a mix with higher voids and insufficient asphalt cement for durability that may experience premature cracking during the life of the pavement (NAPA, 2009).

The Superpave mix design method is a performance-based method, in which the testing and evaluation procedures simulate actual field conditions. Aggregate and binder are tested and checked for acceptance. The trial mixes are compacted in Superpave gyratory compactor at a gyration angle of 1.25°. The vertical pressure for compaction is 600 kPa (87 psi). The number of compaction blows, and the temperature of the material during compaction, varied according to the design requirements. The compaction mold is 150 mm diameter and contains 4700 g of aggregate, with asphalt binder.

Superpave mix design procedures provide guidance on selection of aggregate and asphalt binder. The asphalt binder is based on a performance graded (PG) asphalt binder system, which was developed under Superpave in the mid-1990s. Asphalt binder is typically selected for given climatic conditions and traffic loads. The aggregate properties are selected based on consensus and source properties.

Blast furnace and steel slags, including the basic oxygen furnace (BOF) and the open hearth furnace, have been used in HMA paving since the 1960s, although the earliest use can be traced back to the mid-1940s in England as slag coated macadam (Lee, 1950, 1974). In the initial utilization, it was reported in the comparison of blast furnace slag with BOF slag that BOF slag has demonstrably excellent affinity for bitumen and asphalt concrete mixes containing BOF slag that have a Marshall stability value of 13.5 kN with a flow of 2.25 mm at a bitumen content of 5.7% (Heaton, 1979; Heaton, Richard, Lanigan, & Hart, 1976). Steel slag asphalt mixes combine a very high stability with good flow and excellent stripping resistance. Even with the high stability, the compactibility is still adequate due to the flow and heat retention qualities of the mix. The wear and skid resistance of steel slag asphalt mixes are superior to those of natural aggregate surface course when comparable gradations are used. Test sections, polished stone value (PSV) tests, and accident-skid resistance surveys indicate that steel slag asphalt mixes provide the required skid resistance for both highway and urban situations (Emery, 1982; Kamel & Gartshore, 1982; Noureldin & McDaniel, 1990).

Another benefit of using steel slag as an aggregate comes from the economic value. In terms of highway construction materials dollars, approximately 30% is spent on aggregate, in contrast to 25% on steel, 19% on bituminous materials, 10% on cement, and lesser amounts on miscellaneous items such as pipe, lumber, and petroleum products.

In the last couple of decades, slag use in asphalt paving has been extended to nonferrous slags and nonmetallurgical slags, ferrous nickel slag, copper slag, and boiler slag, for example. The use of slag aggregate in HMA has been expanded to various surface treatments and special mixes, SMA, and CIR, for instance. Research and development has promoted the practical use of slags in construction practices.

10.2 Technical requirements for aggregates in asphalt concrete

When the Superpave design method was developed, pavement experts were surveyed by Strategic Highway Research Program (SHRP) researchers to determine which aggregate properties were most important for HMA. There was general agreement that aggregate properties played an integral role in overcoming permanent deformation. The survey results were used and two categories of properties (ie, consensus and source properties) were identified. Also under Superpave, a new way of specifying the design aggregate gradation was developed. Aggregate requirements for the Superpave HMA mix design system are reviewed here. Some of the properties had been used in Marshall design procedures. Readers may refer to specific specifications for the Marshall mix design method for other special asphalt paving applications.

10.2.1 Consensus properties and measurement

Certain aggregate characteristics are critical to well-performed HMA. These characteristics are called *consensus properties* because there is wide agreement in their use and specified values. The consensus properties are (i) coarse aggregate angularity, (ii) fine aggregate angularity, (iii) flat and elongated particles, and (iv) clay content.

The criteria for these consensus aggregate properties are based on traffic level and position within the pavement structure. Materials close to the pavement surface subjected to high traffic levels require more stringent properties. The criteria are intended to be applied to a proposed aggregate blend rather than individual components. However, many agencies currently apply such requirements to individual aggregates so undesirable components can be identified. The consensus properties are detailed in Table 10.1. In Table 10.1, 100 mm (4 in.) is used to divide the materials position in the pavement structure. ESAL is the acronym for equivalent single axle load. The commonly used equivalent load is 80 kN or 18,000 lb.

Table 10.1 Superpave aggregate consensus property requirements

Design ESALs (in millions)	Coarse aggregate angularity (%), minimum		Uncompacted void content of fine aggregate (%), minimum		Sand equivalent (%), minimum	Flat and elongated (%), maximum
	≤100 mm	>100 mm	≤100 mm	>100 mm		
<0.3	55/–	–/–	–	–	40	–
0.3 to <3	75/–	50/–	40	40	40	10
3 to <10	85/80	60/–	45	40	45	10
10 to <30	105/90	80/75	45	40	45	10
≥30	100/100	100/100	45	45	50	10

Data from AI (2001). Superpave Mix Design. Superpave Series No. 2 (SP-2). 3rd ed. Lexington, KY: Asphalt Institute.

Also in Table 10.1, (i) the design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period (regardless of the actual design life of the roadway, the design ESALs for 20 years should be determined and used); (ii) the first number of coarse aggregate angularity is the percentage of the particle that has one fractured face and the second number is the percentage of the particles that has two or more fractured faces; and (iii) flat and elongated limit is based on a 5:1 maximum-to-minimum ratio (Fig. 10.2).

10.2.1.1 Coarse aggregate angularity

Coarse aggregate angularity is determined by computing the percentage of coarse aggregate particles with fractured faces. A sample of coarse aggregate is divided into three groups. One group contains all the particles with no fractured face, the second group contains all particles with one fractured face, and the third group contains all particles with two or more fractured faces. The percentage with one fractured face and with two or more fractured faces are determined. The test methods are specified in the American Society for Testing and Materials (ASTM) D5821 Standard Test Method for Determining the Percentage of Fracture Particles in Coarse Aggregate.

10.2.1.2 Fine aggregate angularity

The fine aggregate angularity property ensures a high degree of fine aggregate internal friction and rutting resistance. It is defined as the percentage of air voids present in loosely compacted aggregates smaller than 2.36 mm. The test method is specified in the American Association of State Highway and Transportation Officials (AASHTO) T304: Uncompact Void Content of Fine Aggregate. This property is influenced by particle shape, surface texture, and grading. Higher void content means more fractured faces (Poh, Ghataora, & Ghazireh, 2006).

In the test procedure, a sample of fine, washed and dried aggregate is poured into a small calibrated cylinder through a standard funnel. By measuring the mass of fine aggregate (W) in the filled cylinder of known volume (V), the void content can be calculated as the difference between the cylinder volume and fine aggregate volume collected in the cylinder (Fig. 10.1). The fine aggregate bulk specific gravity (G_{sb}) is used to compute the fine aggregate volume (AI, 2001; O'Brien & Haddock, 2009).

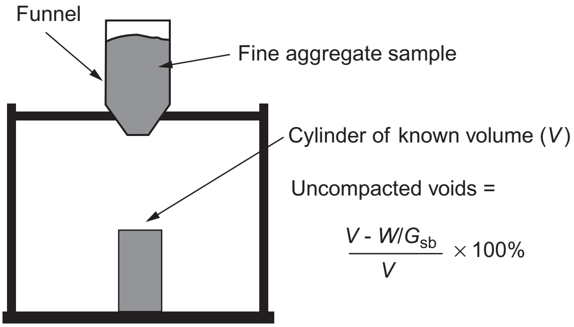

Fig. 10.1 Fine aggregate angularity apparatus.

10.2.1.3 Flat and elongated particles

The flat and elongated particles characteristic is the percentage by mass of coarse aggregates that have a maximum to minimum dimension ratio greater than five. Flat and elongated particles are undesirable because they have a tendency to break during construction and under traffic. Ideally, aggregate particles should be cubical. Flat and elongated particles tend to cause problems with compaction, particle breakage, loss of strength, and segregation.

The test procedure is specified in ASTM D4791: Flat or Elongated Particles in Coarse Aggregate and is performed on coarse aggregate larger than 4.75 mm. The procedure uses a proportional clipper device (Fig. 10.2) to measure the dimensional ratio of a representative sample of aggregate particles. In Fig 10.2, the aggregate particle is first placed with its largest dimension between the swinging arm and fixed post at position A. The swinging arm then remains stationary while the aggregate is placed between the swinging arm and the fixed post at position B. If the aggregate does not fill this gap, then it is counted as a flat or elongated particle.

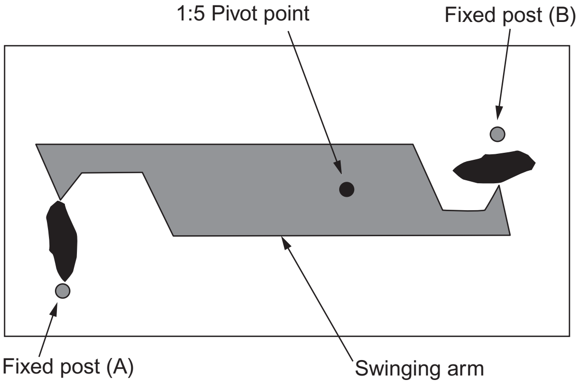

Fig. 10.2 Measuring flat and elongated particles.

10.2.1.4 Sand equivalent

Sand equivalent is used to test clay content, which is the percentage of clay material contained in the aggregate fraction that is finer than a 4.75 mm sieve. It is measured by ASTM D2419: Standard Test Method for Sand Equivalent Value of Soil and Fine Aggregate, or AASHTO T176: Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test.

A sample of fine aggregate is mixed with a flocculating solution in a graduated cylinder and agitated to loosen clayey fines present in and coating the aggregate. The flocculating solution forces the clayey materials into suspension above the granular aggregate. After a settling period, the cylinder height of suspended clay and settled sand is measured (Fig. 10.3). The sand equivalent value is computed as the ratio of the sand to clay height readings, expressed as a percentage.

10.2.2 Source properties and measurement

There are also critical properties of aggregate that could not be reached by consensus because needed values are source specific. Consequently, a set of source properties was recommended. Specified values are established by local agencies. While these properties are relevant during the mix design process, they may also be used as source acceptance control. Those properties are toughness. soundness. and deleterious materials.

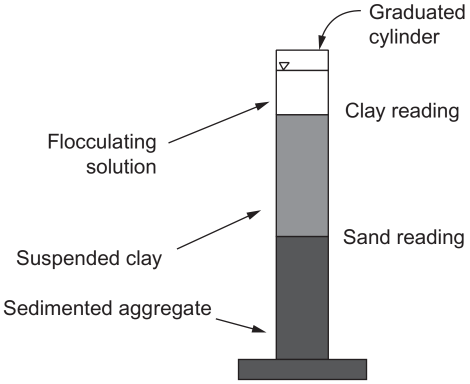

Fig. 10.3 Sand equivalent test.

10.2.2.1 Toughness

Toughness is the percentage loss of material from an aggregate blend during the Los Angeles abrasion test specified in ASTM C131 or C535 and AASHTO T96. This test estimates the resistance of coarse aggregate to abrasion and mechanical degradation during handling, construction, and in-service use. It is performed by subjecting the coarse aggregate, usually larger than 2.36 mm, to impact and grinding by steel spheres. The test result is the mass percentage of coarse material lost during the test due to mechanical degradation. Maximum loss values typically ranges from 35% to 45%.

10.2.2.2 Soundness

Soundness is the percentage loss of material from an aggregate blend during the sodium or magnesium sulfate soundness test. This test, which is specified in ASTM C88 and AASHTO T104, estimates the resistance of aggregate to in-service weathering. It can be performed on both coarse and fine aggregate. The test is performed by exposing an aggregate sample to repeated immersions in saturated solutions of sodium or magnesium sulfate followed by oven drying. One immersion and drying is considered one soundness cycle. During the drying phase, slats precipitate in the permeable void space of the aggregate. Upon reimmersion, slat rehydrates and exerts internal expansive forces that simulate the expansive forces of freezing water.

The rest result is total percentage loss over various sieve intervals for a required number of cycles. Maximum loss values typically range from 10% to 20% for five cycles.

10.2.2.3 Deleterious materials

Deleterious materials are the percentage of contaminates such as clay lumps, shale, wood, mica, and coal in the blended aggregate. The test is specified in ASTM C142 and AASHTO T112. The analysis can be performed on both coarse and fine aggregate. The test is performed by wet sieving aggregate size fractions over specified sieves. The mass percentage of material lost as a result of wet sieving is reported as the percentage of clay lumps and friable particles.

A wide range of criteria for the maximum allowable percentage of deleterious particles exists. Values range from as little as 0.2% to as high as 10%, depending on the exact composition of the contaminant.

10.2.3 Gradation requirements

To specify gradation, the 0.45 power gradation chart is used to define a permissible gradation. The ordinate of the chart is percentage passing. The abscissa is an arithmetic scale of sieve size in mm, raised to the 0.45 power. The maximum density line represents a gradation where the aggregate particles fit together in their densest possible arrangement. Fig. 10.4 shows a 0.45 power gradation chart with a maximum density line for a 19.0 mm maximum size aggregate (12.5 mm nominal maximum aggregate size).

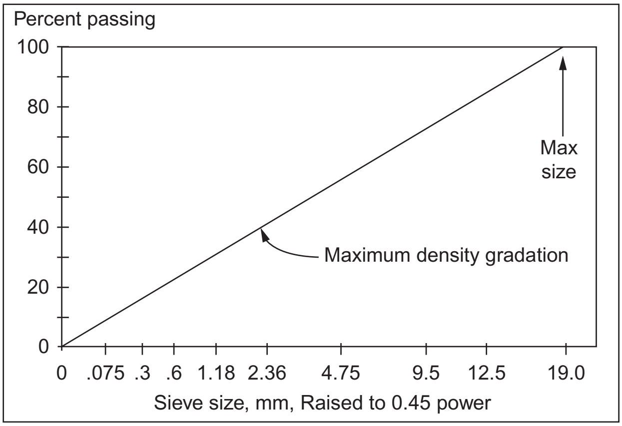

Fig. 10.4 Maximum density line for 19 mm maximum size.

An important feature of the 0.45 power chart is the maximum density gradation. The maximum density line plots as a straight line from the maximum aggregate size to the origin. The maximum size is defined as one sieve size larger than the nominal maximum size, and the nominal maximum size is defined as one sieve size larger than the first sieve to retain more than 10%.

To specify aggregate gradation, two additional features have been added to the 0.45 power chart: control points and a restricted zone.

Control points. Control points function as master ranges through which gradations must pass. Control points are placed at the nominal maximum size, an intermediate size (2.36 mm), and the smallest size (0.075 mm). The control point limits vary depending on the nominal maximum aggregate size of the design mixture.

Restricted zone. The restricted zone resides along the maximum density gradation between the intermediate size (either 4.75 mm or 2.36 mm) and the 0.3 mm size. The restricted zone forms a band through which it is generally recommended that the gradation not pass. Gradations that pass through the restricted zone from below the zone have often been called "humped gradations" because of the characteristic hump in the grading curve that passes through the restricted zone.

In most cases, a humped gradation indicates an oversanded mixture and/or a mixture that possesses too much fine sand in relation to total sand. This gradation often results in tender mix behavior, which is manifested by compaction problems during construction (Table 10.2). These mixtures may also offer reduced resistance to permanent deformation (rutting) during their performance life.

Table 10.2 Superpave mixture gradations

Superpave designation	Nominal maximum size (mm)	Maximum size (mm)
37.5 mm	37.5	50.0
25.0 mm	25.0	37.5
19.0 mm	19.0	25.0
12.5 mm	12.5	19.0
9.5 mm	9.5	12.5

Data from AI (2001). Superpave Mix Design. Superpave Series No. 2 (SP-2). 3rd ed. Lexington, KY: Asphalt Institute.

The numerical gradation limits for the five Superpave mixtures are shown in Table 10.3.

Table 10.3 Superpave aggregate gradation control points

Sieve size, mm	Nominal maximum aggregate size—control point (percent passing)									
	37.5 mm		25.0 mm		19.0 mm		12.5 mm		9.5 mm	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
50.0	100									
37.5	90	100	100							
25.0		90	90	100	100					
19.0				90	90	100	100			
12.5						90	90	100	100	
9.5								90	90	100
4.75										90
2.36	15	41	19	45	23	49	28	58	32	67
0.075	0	6	1	7	2	8	2	10	2	10

Data from AI (2001). Superpave Mix Design. Superpave Series No. 2 (SP-2). 3rd ed. Lexington, KY: Asphalt Institute.

The plasticity characteristics of the fines in an aggregate are also critical for determining their behavior. In asphalt concrete, the fines generally should be nonplastic (Rollings & Rollings, 1996). ASTM D5106 provides the standard specification for steel slag aggregates for HMA (ASTM, 2013a).

10.3 General requirements for asphalt pavements and surface treatment techniques

HMA combines mixing materials and is placed and compacted on the job site for best performance. The required performance includes permanent deformation resistance, skid resistance, fatigue resistance, low-temperature cracking resistance, and moisture-induced damage resistance. Resistance to permanent deformation and skid resistance are predominately controlled by the quality of the aggregate. Fatigue resistance and low-temperature cracking resistance are generally considered to be related to asphalt binder properties. However, recent research has shown that using slag aggregate to replace natural aggregate can improve fatigue and low-temperature behavior of HMA and minimize moisture-induced damage.

10.3.1 General performance requirements for asphalt pavement structure

A good pavement required by users should be strong, durable, smooth, safe, and economical. Slag aggregates can make positive contributions to all these aspects during the service life of the pavement that contains slag aggregate.

10.3.1.1 Resistance to permeant deformation

Permeant deformation mostly refers to pavement rutting, which is controlled by selecting quality aggregates with proper gradation and the optimal content of asphalt binder so that adequate voids exist in the mix. The proper grade of asphalt binder must also be selected to ensure that excessive rutting and bleeding (flushing) do not occur during the hot weather months when the viscosity of the asphalt cement binder is low and the traffic load is primarily carried by the mineral aggregate structure. Ruts are depressions that occur in the pavement's wheel path as a result of traffic loads. There are three types of asphalt pavement rutting: wheel path wear and densification (construction) rutting; pavement structural rutting; and asphalt concrete instability rutting (permanent deformation). The rutting of most concern is asphalt concrete instability rutting (NRC, 2003). Asphalt mix with a high amount of natural sand and inadequately crushed gravels tends to have low resistance to shear and is prone to excessive rutting. Generally, crushed coarse and fine aggregates mixtures with lower total asphalt content will have more resistance to permanent deformation. Less than 12% of fine aggregate for expressway pavement and major urban intersections are appropriate to resist rutting. It is reported that in an asphalt concrete airfield taxiway in the western United States, the natural sand content was increased from the specified maximum of 15% of the aggregate to 30%. In less than one year, the pavement was badly rutted and cracked because of the lowered stability of the asphalt concrete with the high proportion of rounded natural sand particles (Rollings & Rollings, 1996). In contrast, slag aggregate is crushed with the rough surface texture that is needed by HMA to prevent rutting.

To predict or investigate permanent deformation of HMA mixes, test methods such as static or dynamic creep or wheel tracking tests can be used for new HMA mixes or specimens from the field to evaluate the quality or the rutting that occurred. Fig. 10.5 is an Asphalt Pavement Analyzer (APA), which can be used for HMA rutting resistance and also the fatigue behavior of HMA mixes and pavements from field.

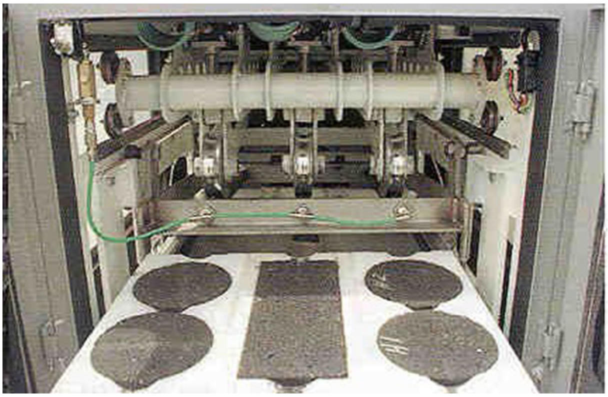

Fig. 10.5 Asphalt Pavement Analyzer.

10.3.1.2 Friction or skid resistance

Friction or skid resistance is an important safety factor for highway pavement and airport runways that is accounted for in proper materials selection, design, and construction. In pavement management, friction is a measure of serviceability. In life cycle cost analysis, the cost of restoring friction is normally considered.

Friction is defined as (ASTM, 2011)

$$SN = F / W \times 100 \tag{10.1}$$

where SN = skid number; F = traffic force (horizontal force applied to the test tire at the tire–pavement contact patch, Newton or lb; W = dynamic vertical load on the test wheel, Newton or lb.

Friction is only required for surface mixes that must be designed to provide sufficient resistance to sliding to permit normal turning and braking movements to occur. Aggregate texture, shape, size, and resistance to polish are required characteristics for skid resistance. Also, the mix should not contain such high asphalt cement content that bleeding may occur, creating a slippery surface.

Friction can be determined by a number of methods including the locked trailer method that is specified in ASTM E 274: Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire, and portable frictions devices that can be used both in the laboratory and the field to measure friction (eg, British Portable Tester, California Skid Tester). These testers are most sensitive to microtexture. Blast furnace and steel slag aggregates have rough microtextures that are different from those of natural aggregates such as limestone, sandstone, and gravel, and therefore have widely differing friction qualities.

10.3.1.3 Fatigue resistance

HMA pavement should not crack when subjected to repeated loads over a period of time, especially from the bottom layer of the HMA (bottom-up cracking). Fatigue is traditionally considered to be a pavement structure design issue and not normally controlled in the HMA mix design process. However many research results have shown that both asphalt and aggregate can affect fatigue behavior of HMA. For example, higher asphalt content and/or using polymer modified asphalt (PMA) have more resistance to fatigue damage and using steel slag aggregate can also minimize fatigue failure (Ali, Chart, Papagiannakis, Theriault, & Bergan, 1992; Bagampadde, Wahhab, & Aiban, 1999; Huang, Bird, & Heidrich, 2007; Kavussi & Qazizadeh, 2014; Lu & Li, 2012; Pasetto & Baldo, 2010; Pasetto & Baldo, 2011, 2012a, 2012b; Xue, Hou, Zhu, & Zha, 2009). Complex repeated load tests can be used to estimate the number of cycles to cause fatigue failure of HMA specimens. APA can also be used for this purpose.

10.3.1.4 Resistance to low-temperature cracking

Resistance to low-temperature cracking is a HMA mix property important in cold regions having low ambient temperatures. Low-temperature cracking of HMA pavement is primarily influenced by the low-temperature properties of asphalt cement. The selection of the proper binder will minimize the problem. It is also reported that steel slag HMA has improved low-temperature behavior (Xue et al., 2009).

10.3.1.5 Resistance to moisture induced damage (stripping resistance)

Some HMA mixes, when subjected to moisture or water, lose adhesion between the aggregate surface and asphalt cement binder. Aggregate properties are responsible for this phenomenon. Normally, antistripping agents are used if stripping will occur. Steel slag has some level of free lime, which makes it a good aggregate in stripping resistance (Emery, 1976a, 1984; Heaton, 1979). It is also suggested by Ongel, Harvey, and Kohler (2008) that 2% of free lime in steel slag is appropriate for striping resistance.

10.3.1.6 Workability (compactibility)

HMA mix must be capable of being placed and compacted with reasonable effort. No test method is currently available to quantify workability during the laboratory mix design phase. Workability problems are most frequently discovered during paving operations. Suitable adjustments to the mix design can be made quickly to overcome workability problems. Generally, finer mixtures with relatively high asphalt content have better workability than coarser mixtures and mixtures with low asphalt contents (NAPA, 2009).

10.3.2 Surface treatment techniques and requirements

As many pavements reach their terminal serviceability, it is becoming increasingly important to extend pavement service life in the most cost-effective manner. Various surface rehabilitation or maintenance techniques have been developed to extend the service life of both low volume roads and heavily traveled roads to improve the functions of the pavement.

Surface rehabilitation techniques can be categorized into three types: (i) thin seals/mixtures, sand seal, slurry seal, and microsurfacing, for instance; (ii) chip seal coats, including single and multiple layer chip coats; and (iii) thin hot mix overlay (eg, open graded and dense graded courses).

10.3.2.1 Sand seal

Sand seal is an application of asphalt cement covered by a fine (sand) aggregate. Its purpose is to seal the surface and provide enrichment of oxidized asphalt surfaces that become dry and brittle with age. It prevents pavements raveling and provides better surface friction. Usually, rapid setting or medium setting emulsions are used. The rate of emulsion application varies from 0.68 to 0.90 l/m^2 (0.15–0.2 gal/yd^2) depending on pavement texture, local conditions, and traffic.

10.3.2.2 Slurry seal

Slurry seal is a mixture of well-graded fine aggregate with mineral filler and dilute asphalt emulsion. A single course is usually applied in thicknesses of 3–6 mm (1/8–1/4 in.). Slurry seals are effective in areas of excessive oxidation and hardening of the existing asphalt and are used for sealing minor surface cracks and voids, retarding surface raveling, delineating different pavement surface areas, and, with proper aggregate, improving surface friction characteristics.

Aggregate, water, emulsion (slow or quick setting), and additive are proportionately mixed together in a slurry machine on the job site and immediately applied to the paved surface with a squeegee device. Additives such as Portland cement, hydrated lime, or aluminum sulfate liquids are often used in small quantities as stabilizers or chemical modifiers to aid in setting the slurry.

There are three types of slurry seal, which primarily differ by the gradation of the aggregate used. Table 10.4 presents slurry mixture characteristics recommended by the International Slurry Surfacing Association (ISSA). Types II and III are used in moderate to heavy traffic to correct raveling and obtain maximum skid resistance and an improved wearing surface.

10.3.2.3 Microsurfacing

Microsurfacing is a polymer-modified cold paving slurry seal system. Its most common uses are restoration of skid resistant wearing surfaces and leveling. The polymer-modified slurry cures and develops strength faster; therefore, it can be placed in greater thicknesses.

Microsurfacing consists of a mixture of latex-modified emulsified asphalt, mineral aggregate, mineral filler, water, and additives. The modifier used in this treatment could be either natural latex or synthetic latex. Most US state specifications require that the mixture include 82–90% aggregate and 2–4% latex polymer by

Table 10.4 **Slurry mixture characteristics**

Type of slurry	**I**	**II**	**III**
Sieve size mm (in.)	**Percent passing**		
9.5	100	100	100
4.75	100	90–100	70–90
2.36	90–100	65–90	45–70
1.18	65–90	45–70	28–50
0.600	40–65	30–50	19–34
0.300	25–42	18–30	12–25
0.150	15–30	10–21	7–18
0.075	10–20	5–15	5–15
Residual asphalt, percent weight of dry aggregate	10–16	7.5–13.5	6.5–12
Application rate, kg/m^2 (lb/yd^2)	3–5.5 (6–10)	5.5–8 (10–15)	8 (15) or more
General usage	Crack sealing (low traffic areas)	Correct raveling, oxidation (moderate to heavy traffic)	Fills minor surface irregularities. Restores surface friction. First course in multicourse applications for heavy traffic

Data from FHWA (1992). An overview of surface rehabilitation techniques for asphalt pavements Pub. FHWA-PD-92-008. Washington, DC: Federal Highway Administration (FHWA).

weight of the asphalt used. The amounts of other constituents as a percentage of the dry aggregate generally are 1.5–3.0% non–air-entrained Portland cement as mineral filler and 6.0–11% residual asphalt. Table 10.5 presents the aggregates gradation requirements for slurry seal in the United States and several European countries.

10.3.2.4 Chip seal

Chip seal is an application of asphalt followed with an aggregate cover. This type of surface treatment can consist of single or multiple layers in thicknesses from 9.5 to 37 mm (3/8 to 1 1/2 in.). Two layers are referred to as a double and three as a triple chip seal coat. In multiple chip seals, smaller aggregate sizes are used in each successive layer; that is, the largest size stones are placed in the first course and these determine the surface layer thickness, and the second course serves to fill the voids in the first course. When using multiple layers, the first layer should be cured before the application of the second layer. Chip seals can be used on both low volume and higher volume roads (volume greater than 5000 vehicles/lane/day) as a wearing course or as the only surface course. Because of

Table 10.5 Composition of US and European modified slurry seal

Country	United States	Germany	Denmark	Italy	Netherlands
Type	**III**	**0–8**	**0–8**	**0–9**	**0–8**
Sieve size	**Percent passing**				
9.5 (3/8 in.)	100			85–100	95–100
8.0 (5/16 in.)		90–100			90–100
6.25 (1/4 in.)			93		67–90
4.75 (No. 4)	70–90	65–85			
4.0 (No. 5)				60–85	55–80
2.36 (No. 8)	45–70				
2.00 (No. 10)		45–65	50	36–55	40–60
1.18 (No. 16)	28–50				
0.60 (No. 30)	19–34				
0.40 (No. 40)				14–28	
0.30 (No. 50)	12–25				
0.25 (No. 60)			17		
0.20 (No. 70)					
0.15 (No. 100)	7–18				
0.075 (No. 200)	5–15	6–12	3	4–8	2–10
Residual asphalt, (% of dry aggregate	5.5–9.5	5–7	5.3	5.5–7.5	5–7
Application rate, kg/m2 (lb/yd^2)	8.1–16.2 (15–30)	25–30 (46–55)	>16–18 (>29–33)	15–25 (28–46)	

Data from FHWA (1992). An overview of surface rehabilitation techniques for asphalt pavements Pub. FHWA-PD-92-008. Washington, DC: Federal Highway Administration (FHWA).

its ability to waterproof the surface, it provides low severity crack sealing, and improves surface friction. The use of precoated chips is more suitable for high volume roads. Application usually consists of a spray of rapid-setting type emulsion (or asphalt cement, cutback) at a relatively high rate, followed immediately by an application of aggregates. Emulsions are preferred over asphalt cements and cutbacks. The asphalt application rate is determined to achieve an embedment of 50–70%. Maximum aggregate sizes usually range from coarser than sand up to 19 mm (3/4 in.). One-size aggregates are preferred because they develop better interlocking and provide maximum contact between the tire and the surface. Table 10.6 gives example of quantities of asphalt and aggregate for single chip seals applications with respect to the commonly used aggregate sizes. The cover aggregate is rolled immediately after spreading with either a steel-wheeled tandem or rubber-tired roller to ensure maximum embedment. The rubber-tired roller is often thought to be the best all-purpose roller for chip seal construction (FHWA, 1992).

Table 10.6 **Quantities of asphalt and aggregate for single chip seal application**

Nominal size of aggregate mm (in.)	Quantity of aggregate kg/m^2 (lb/yd^2)	Quantity of emulsion l/m^2 (gal/yd^2)
19–9.5 (3/4–3/8)	22–27 (40–50)	1.8–2.3 (0.4–0.5)
12.5–4.5 (1/2-No. 4)	14–16 (25–30)	1.4–2.0 (0.30–0.45)
9.5–2.36 (3/8-No.8)	11–14 (20–25)	0.9–1.6 (0.20–0.35)
4.75–1.18 (No. 4-No. 16)	8–11 (15–20)	0.7–0.9 (0.15–0.20)

Data from FHWA (1992). An overview of surface rehabilitation techniques for asphalt pavements Pub. FHWA-PD-92-008. Washington, DC: Federal Highway Administration (FHWA).

10.3.2.5 Open graded friction course

Open graded friction courses (OGFCs), also known as porous friction courses (PFCs), are normally less than 25 mm (1 in.) thick and possess high percentages of voids (15%). High voids in an OGFC allow water to drain through the mix and laterally to the side of the road. This rapid removal of water reduces the potential for hydroplaning and improves visibility by reducing tire spray, and substantially improves the surface friction characteristics. They may also reduce the roadway noise that is a function of the air voids and the maximum stone size at the surface. The gradation of this treatment is characterized by an open graded mix with a nominal maximum size of 9.5 mm (3/8 in.), and a high proportion of single-sized aggregate, with about 2–5% passing 0.075 mm (No. 200) sieve to reduce binder runoff and improve mix stability. An OGFC generally has a higher asphalt content than a dense graded mix.

10.3.2.6 Stone mastic (matrix) asphalt

SMA is a relatively thin (12.5–40 mm) gap-graded, densely compacted, HMA that is used as a surface course on both new construction and surface renewal. It is a mixture of asphalt cement, coarse aggregate, crushed sand, and additives. These mixes are different from normal dense grade HMA mixes in that there is a much greater amount of coarse aggregate in the SMA mix. It can be used on major highways with heavy traffic volumes. This product provides a rut resistant wearing course and resistance to the abrasive action of studded tires. This application also provides slow aging and good low-temperature performance.

SMA is used to maximize the interaction and contact among the coarse aggregate fraction in HMA. Asphalt cement and finer aggregate portions provide the mastic that holds the stone in close contact. Typical mix design will generally have 6.0–7.0% medium-grade asphalt cement (or polymer-modified AC), 8–13% filler, 70% minimum aggregate greater than 2 mm (No 10) sieve, and 0.3–1.5% fibers by weight of mix. Fibers are generally used to stabilize the mastic and this reduces the drain off of binder in the mix. Voids are normally kept between 3% and 4%. Maximum particle sizes range from 5 to 20 mm (0.2 to 0.8 in.).

Mixing, transportation, and placement of SMA use the customary equipment and practices with some variations. For example, higher mixing temperature of about 175°C (347°F) is usually necessary because of coarser aggregate, additives, and relatively high viscosity asphalt in SMA mixes. Also, when cellulose fibers are used, the mixing time has to be increased to allow for proper mixing. Rolling begins immediately after placement to achieve density quickly before the mix temperature decreases significantly. Compaction is usually accomplished by use of 9–11 tonne (10–12 ton) steel-wheeled rollers. Vibratory rolling may also be used with caution. Compared to normal dense-graded HMA, SMA has better shear resistance, abrasion resistance, cracking resistance, and skid resistance, and is equal for noise generation. Table 10.7 represents the comparison of the gradation of SMA used in the United States and Europe.

Table 10.7 **Composition of US and European SMA mixes**

Country	**United States**	**Germany**	**Sweden**	**Denmark**	**Norway**
Type	**0–11**	**0–11**	**0–12**	**0–12**	**0–11**
Sieve size	**Percent passing**				
19 (5/8 in.)					
12.5 (1/2 in.)	85–95				
11.0 (7/16 in.)		90–100	95	93	80–100
9.5 (3/8 in.)	60–75				
8.0 (5/16 in.)		50–75	38–50	53	47–64
5.0 (No. 4)	25–34	30–50			
4.0 (No. 5)			30	28	30–45
2.36 (No. 8)	18–24				
2.00 (No. 10)		20–30	20–26	18–28	20–32
0.33 (No. 50)	12–15				
0.09 (No. 175)		8–13		4 min	
0.075 (No. 200)	8–12		10		9–14
Asphalt (% of mix)	6–7	6.5–6.8	6.5–6.8	6.5–6.9	6.3
Fibers (% of mix)	Cellulose (0.3) Mineral (0.4)	Cellulose (0.3)	Cellulose (0.3) Mineral (0.5)	Cellulose (0.3)	Cellulose (0.3)

Data from FHWA (1992). An overview of surface rehabilitation techniques for asphalt pavements Pub. FHWA-PD-92-008. Washington, DC: Federal Highway Administration (FHWA).

10.3.3 Construction procedures

The objective of HMA paving is to produce a finished pavement meeting the specified design requirements. HMA paving involves production, hauling, placement, and compaction steps. Quality control is conducted during the entire process. Aggregates are dried and weighted, and asphalt cement is weighted and mixed with dried proportioned aggregates in the plants (batch plant or drum plant).

Discharged HMA is hauled from the plant to the construction site by trucks, such as bottom dump trucks or tandem axle end dump trucks, which have metal beds, to be cleaned of foreign material and hardened asphalt. Pavers pull up to meet the trucks. During delivery the driver must direct the truck squarely against the paver, and should stop the truck a few inches in front of the paver. The truck bed is slowly raised. If the mix is dumped too quickly segregation can occur.

A material transfer device (MTD) is more frequently used between the dump truck and paver to keep the operation flowing smoothly, maintain the required temperature, and avoid segregation.

Surface preparation is needed before placing HMA materials by applying a prime coat or tack coat. A prime coat is applied to an unbound surface, using moderate, uniform application of low-viscosity liquid asphalt. A tack coat is applied to a bound surface using light, uniform application of liquid asphalt or asphalt emulsion.

Compaction is essential to good performance of pavement. Pavement needs to be compacted to a desirable air voids level. Required compaction can only be achieved if mixture is confined and mixture is hot (workable). Factors affecting compaction include mixture properties, base and subgrade support (confinement), ambient conditions, and lift thickness. Compaction must be completed while mix temperature exceeds 85°C (185°F) for neat binders, and 115°C (240°F) for modified binders.

Compaction equipment used for HMA paving include vibratory steel wheeled, pneumatic, static steel-wheeled. Vibratory rollers are commonly used for initial (breakdown) rolling. For thin overlays (≤2 in.) low amplitude or static mode is used. Lighter rollers and static steel-wheeled rollers are normally used for finish rolling. Drums must be smooth and clean. For initial compaction, the drive wheel must face the paver.

Pneumatic tire rolling manipulates mat under and between tires and tight finish resists moisture penetration. During paving the paver speed must not exceed that of the compaction operation. A nuclear gauge is commonly used to checking density (ie, compaction values) of HMA. Fig. 10.6 presents the sequence of compaction of HMA pavement.

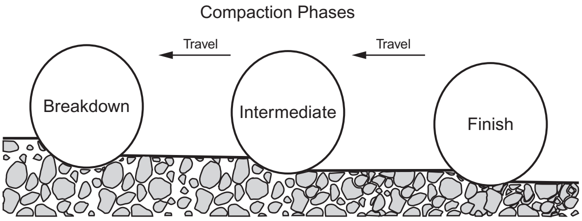

Fig. 10.6 Compaction of HMA.

10.4 Practical use of slag in asphalt paving

Various slag can be processed into coarse and fine aggregates for use in dense or open graded HMA, and in cold mix or surface treatment. In this regard, steel slag has been the pioneer of the utilization of slag in asphalt paving. Proper processing of slag and special quality control procedures are extremely important in the use of slag in asphalt paving applications. Of particular importance is the potential for volumetric expansion, especially for steel slag, and also other nonferrous slags that contain free lime and periclase, which could result in pavement cracking if ignored.

In addition to blast furnace slag and steel slag, a variety of nonferrous slags (air-cooled or granulated) including phosphorus, copper, nickel, and zinc slags can be used as coarse or fine aggregate in HMA pavements and surface treatment. Processed air-cooled and granulated copper, nickel, and phosphorus slags have good soundness characteristics, abrasion resistance, and high friction angle due to a sharp, angular shape. However, some nonferrous slags are vitreous or "glassy," which can adversely affect their frictional resistance properties. Some glassy nonferrous slags may also be susceptible to moisture-related damage (stripping) (Chesner, Collins, & MacKay, 1998).

10.4.1 Steel slag use in hot-mix asphalt

10.4.1.1 Early development of slag use in asphalt paving

The technology of slag use in asphalt paving has experienced its early development stages. In the 1960s, the British company Steelphalt produced HMA and coated chipping mixes using electric arc furnace (EAF) steel slag from the British Steel Corporation plants at Rotherham and Scunthorpe. The EAF slag was stored for 1 year in large heaps before processing for steel recovery, sizing, and incorporation into asphalt mixes in two fully automated batch plants. Asphalt concrete mixes were produced in the usual manner and met the appropriate specifications. The chippings were coated with asphalt cement in a batch plant pugmill and sprayed with cooling water when discharged from the pugmill. An important application was on the M62 highway where 19 mm coated chippings were used in 1969 with excellent results.

In the 1960s, the Levy Company in the United States produced 9.5 mm open hearth furnace slag asphalt concrete mix for paving in parking and industrial areas. Since that time, steel slag asphalt concrete mixes have achieved wide acceptance in this region. A procedure of watering the steel slag and storing it for at least 1 month before use was adopted to eliminate minor surface popouts.

In 1969, steel slag was used in asphalt concrete mixes in the Hamilton–Toronto area in Ontario, Canada. The city of Hamilton specifications included 9.5 mm steel slag asphalt mix. Steel slag was used in hot mixes for winter patching, which demonstrated that steel slag was usually fairly dry so heating costs were reduced; steel slag asphalt concrete retained its heat very well so that a patching crew could handle large batches and the high unit weight and stability of steel slag asphalt concrete held patches.

10.4.1.2 Recent development

Along with the development of steelmaking, slag processing, and treating technology, more EAF slag has been produced and used in various paving applications that are the main focuses on slag research (Hainin et al., 2014).

In the last couple of decades, other types of slag have been used in asphalt paving; for example, ferronickel slag (Wang, Thompson, & Wang, 2011), copper slag (Collins & Cielieski, 1994; Gorai, Jana, & Premchand, 2003), and boiler slag (Chesner et al., 1998).

10.4.1.3 Marshall stability

Steel slag HMA offers high stability, which is a distinct advantage for applications where rutting resistance is required, such as for roads within steelworks, industrial parking areas subjected to heavy axle loading, expressways, major urban roads, bus bays, and intersections. Thinner steel slag HMA layer can provide satisfactory performance that sometimes ordinary mixes may not perform under heavy traffic.

10.4.1.4 Permanent deformation prevention

Processed steel slag aggregate processes angular shape and rough texture surface, which give steel slag the ability to substitute aggregates in asphalt mix where stability (resistance to rutting) and skid resistance are concerned. HMA durability (resistance to moisture, fatigue) can also be improved when slag aggregates are used (Huang et al., 2007; Pasetto & Baldo, 2014; Yi, 2008).

10.4.1.5 Skid resistance

Experience with steel slag HMA mixes in many countries has indicated that skid resistance is very satisfactory for most applications (Likoydis & Liapis, 2011; Ramaswamy, Tanaboriboon, & Kheok, 1986; Stock, Taylor, & Ibberson, 1996). PSVs for typical natural aggregates support the findings that steel slag and blast furnace slag are superior to many natural aggregates. The wet road accident rate did not significantly exceed the dry road accident rate for steel slag HMA surfacing, while the reverse was generally true for other surfacing materials.

10.4.1.6 Free lime and antistripping

The free lime associated with steel slag results in an excellent resistance to stripping of asphalt cement from the aggregate for a range of asphalt cement sources and penetrations. This resistance to stripping is important because it ensures that water will not penetrate to the steel slag in asphalt mixes and initiate potential free lime and/or magnesium oxide expansion problems.

10.4.1.7 Optimum slag replacement

The slag proportion of replacement of natural aggregates is an important factor affecting successful use. The optimum proportion should be decided based on laboratory tests on selected proportioned mixed for a specific slag. In general, steel slag used in paving mixes should be limited to replacement of either the fine or coarse aggregate fraction, but not both, because HMA containing 100% steel slag is susceptible to high void space, overasphalting during production, and subsequent flushing due to in-service traffic compaction (Chesner et al., 1998). However, different research results from specific slag use suggest a different replacement ratio. For example, it is reported that (i) 100% BOF slag is the optimum substitution percentage based on Duncan's multiple range statistical analysis that processes highest skid resistance, better striping resistance, and better permanent deformation (rutting) resistance (Shen, Wu, & Du, 2009); (ii) 80% EAF slag is the best proportion (Oluwasola, Hainin, & Aziz, 2015); (iii) 30% EAF slag replacement presents the best skid resistance number (Asi, 2007); (iv) replacing up to 75% of limestone coarse aggregate by steel slag aggregate improves the mechanical properties of the HMA mixes, however, 25% replacement was the optimal replacement level (Asi, Qasrawi, & Shalabi, 2007); (v) Kavussi and Qazizadeh (2014) reported that increased slag contents in asphalt mixes resulted in increased Marshall stability and Marshall quotient and the fatigue life of the mixes containing EAF slag have greater fatigue life than control mixes; and (vi) Oregon used 30% steel slag to replace natural aggregate HMA concrete (Hunt & Boyle, 2000). To sum up, it is critically important to determine the optimum replacement ratio based on laboratory testing on a specific slag and its usage.

10.4.1.8 Compactibility

Steel slag HMA, with high stability, has reasonable compactibility. The ratio of Marshall stability to flow is related to compactibility. Reasonable compactibility is associated with a low ratio. High flows of steel slag HMA typically result in a reasonable stability to flow ratio. Also, their heat retention and consequent time for compacting is excellent as the rate of cooling is about two-thirds that of natural aggregate asphalt mixes in the key placement and compaction temperature range of 135°C down to 90°C. This combination of favorable stability to flow ratio and heat retention, coupled with inherent stability that permits the breakdown roller to stay close to the paver, generally ensures adequate compaction of steel slag asphalt concrete as confirmed by field experience.

10.4.1.9 Life cycle cost analysis

Mroueh, Eskola, and Laine-Ylijoki (2001) conducted a life cycle cost analysis for road construction focusing on environmental loadings of construction. The study indicated that the use of blast furnace slag can decrease the environmental loadings compared to the reference natural construction materials used.

10.4.2 Other ferrous, nonferrous, and nonmetallurgical slag use in hot-mix asphalt

10.4.2.1 Air-cooled blast furnace slag

Air-cooled blast furnace slag (ACBFS) has been considered by many specifying agencies to be a conventional aggregate and has been used to replace both coarse and fine aggregates in HMA and surface treatment. 12.5 mm (1/2 in.) thick epoxy asphalt with open graded ACBFS pavement were used in two large test areas on the heavily traveled San Francisco-Oakland Bay Bridge. This ACBFS and epoxy asphalt skid-resistant treatment performed well and provided increased skid and hydroplaning resistance, low increase in dead loads, and superior structural properties, in spite of minor localized raveling attributed to inadequate compaction in isolated areas due to cold temperatures at the time of placing. The accident history had improved substantially in the resurfaced areas since ACBFS was used in the surface treatment (Brewer, 1971). In HMA uses, ACBFS is more absorptive than conventional aggregate and therefore has a higher asphalt cement demand. It also has lower compacted unit weight than conventional mineral aggregates, which results in a higher asphalt pavement yield (greater volume for the same weight) (Chesner et al., 1998).

10.4.2.2 Copper slag

Air-cooled copper slag has a black color and glassy appearance. The specific gravity varies with iron content, from a low of 2.8 to as high as 3.8. The absorption capacity of the material is typically very low (0.13%). Granulated copper slag is more porous and therefore has lower specific gravity and higher absorption capacity than air-cooled copper slag. The granulated copper slag is made up of regularly shaped, angular particles, mostly between 4.75 and 0.075 mm (No. 200 sieve) in size. The air-cooled and granulated copper slag has a number of favorable mechanical properties for aggregate use, including excellent soundness characteristics, good abrasion resistance, and good stability. It has high friction angle due to a sharp angular shape. However, the slag tends to be vitreous or “glassy,” which adversely affects its frictional properties (skid resistance), a potential problem if used in pavement surfaces. Some physical and mechanical properties of copper slag are shown in Table 10.8.

Table 10.8 Typical physical and mechanical properties of copper slag

Appearance	Black, glassy, more vesicular when granulated
Unit weight	2800–3800 kg/m^3
Absorption, %	0.13
Bulk density	144–162 lbs per cubic feet
Conductivity	500 ms/cm
Sp. gravity	2.8–3.8
Hardness	6–7 Moh
Moisture	<5%
Water soluble chloride	<50 ppm
Abrasion loss, %	24.1
Sodium sulfate soundness loss, %	0.90
Angle of internal friction	40_/53

Data from Gorai, B., Jana, R. K., & Premchand (2003). Characteristics and utilization of copper slag—a review. *Resources, Conservation and Recycling 39* (2003), 299–313.

Fine copper slag has reportedly been used in HMA pavements in California and granulated copper slag has been incorporated into asphalt mixes in Georgia to improve stability. Michigan Department of Transportation Specifications consider reverberatory copper slag to be a conventional coarse and fine aggregate for HMA pavement (Gorai et al., 2003).

10.4.2.3 Nickel slag

It has been reported that air-cooled and granulated ferronickel slag has been used in different highway construction projects, in Drenas, Kosovo, and Dominican Republic, for example (Ibrahimi, Rizaj, Deva, & Sallahi, 2011; Wang et al., 2011). Air-cooled and granulated nickel slag from Feronikeli production in Drenas, Kosovo, conforms to the local technical standard requirements and is permitted to be used in surface course of asphalt pavement. The skid resistance, depth of surface texture, and water absorption of the asphalt surface have better performance than traditional surfaces. A case study of the use of air-cooled ferronickel slag in highway construction is presented in Chapter 14.

10.4.2.4 Municipal solid waste incineration slag aggregate

Municipal solid waste (MSW) aggregate was used in asphalt concrete (Styton, Gustin, & Viness, 1993) to examine the physical properties and durability. The results indicate that stability values are well above minimum requirements with ordinary aggregate. The physical properties are shown in Table 10.9.

Table 10.9 **Properties of asphaltic concrete containing MSW aggregate**

	Mix # 1	Mix # 2	Mix # 3	Mix # 4
Asphalt cement content, % of total mix	5.2	5.7	6.1	6.6
Bulk specific gravity dry	2.169	2.183	2.187	2.192
Theoretical maximum specific gravity (Gmm)	2.311	2.295	2.282	2.269
Air-voids, %	6.2	4.9	4.2	3.4
Voids filled w/asphalt, %	64.1	71.1	75.6	80.4
Marshall stability, lb (N)	2150 (9560)	2540 (11,300)	2500 (11,120)	2140 (9520)
Flow, 0.01 in (mm)	4 (1.02)	7 (1.78)	7 (1.78)	10 (2.54)

Data from Styton, R. W., Gustin, F. H., & Viness, T. L. (1993). MSW Ash aggregate for use in asphalt concrete. In Waller, H.F., editor. Use of waste materials in hot-mix asphalt, ASTM STP 1193. Philadelphia, PA: ASTM.

Results of the various laboratory tests performed indicate that the MSW aggregate performed well in asphalt pavement. The durability test results are similar to those of ordinary HMA.

Xue et al. (2009) used MSW incinerator ash and slag as a partial replacement of fine aggregate or mineral filler in SMA mixture. Both Superpave and Marshall mix design procedures were carried out. In all the performed tests Superpave mixtures proved their superiority over Marshall mixtures. A Toxicity Characteristic Leachate Procedure (TCLP) test for environmental impact indicated that asphalt is an effective stabilizing and solidifying agent for heavy metal in MSW ash and slag. The heavy metal leachates in TCLP tests have great positive correlation with their initial concentration in waste.

10.4.3 Slag use in surface treatment and other paving applications

10.4.3.1 Stone Mastic Matrix (SMA)

Coarse BOF slag aggregates, which underwent three years of aging before using, were used in SMA mix design (Wu, Xue, Ye, & Chen, 2007; Xie et al., 2012; Xue, Wu, Hou, & Zha, 2006). The percentages of each fraction used to replace basalt stone aggregate are given in Table 10.10. Physical properties of the aggregate used are shown in Table 10.11.

Table 10.10 **Particle size and replacement rate in SMA**

Grain size	Materials	Proportion
9.5–16 mm	BOF slag	48%
4.75–9.5 mm	BOF slag	24%
2.36–4.75 mm	Basalt stone	6%
<2.36 mm	Basalt stone	11%
<0.075 mm	Mineral filler	11%

Data from Wu, S., Xue, Y., Ye, Q., & Chen, Y. (2007). Utilization of steel slag as aggregate for stone mastic asphalt (SMA) mixtures. *Building and Environment, 42* (2007), 2580–2585.

The voids in the mineral aggregate (VMA) is 18.5% and 18.7% for steel slag and basalt SMA, respectively. Steel slag SMA has high temperature stability. The test road has shown excellent performance after 3 years' service with abrasion and friction coefficient of 55 BPN and surface texture depth of 0.8 mm design.

Pasetto and Baldo (2012a, 2012b) used EAF slag in SMA. The SMA mixtures with EAF slag satisfied the local technical standards, and presented higher mechanical characteristics than those of the corresponding asphalts with natural aggregate.

Different types of SMA have been produced. Hainina, Rusbintardjob, Aziza, Hamimc, and Yusoff (2013) used SMA14 and SMA20; while Son, Al-Qadi, and Zehr (2015) used SMA4.75. The engineering cost-benefit analysis with respect to performances from both laboratory and field studies suggests the proper application of 4.75 mm SMA as an efficient and cost-effective wearing course for asphalt thin overlays.

Table 10.11 Physical properties of the aggregates in SMA

Materials	Bulk density (g/cm³)	Water absorption (%)	Crushing value (%)	Polished stone value (%)	Binder adhesion (%)	LA abrasion (%)
BOF slag	3.30	1.29	12.1	58	≥95	13.2
Basalt	2.85	0.68	12.7	48	≥85	15.8

Data from Wu, S., Xue, Y., Ye, Q., & Chen, Y. (2007). Utilization of steel slag as aggregate for stone mastic asphalt (SMA) mixtures. *Building and Environment, 42* (2007), 2580–2585.

10.4.3.2 Porous pavement

Steel slag is an excellent aggregate for porous asphalt mixes. Porous HMA can be 45–55 mm thick, and placed over an impermeable layer to protect underlying layers from the penetration of water. A dense layer is normally required beneath the porous asphalt layer. An emulsion or a polymer-modified bond should be applied between the porous surface and the underlying layer. A polymer modifier or fiber additive is specified to reduce draindown of porous asphalt mixes (Ongel et al., 2008). Research conducted by Hainin, Rusbintardjo, Hameed, Hassan, and Yusoff (2014) indicated that the steel slag porous HMA meets all specified requirements. In addition, steel slag mixes possess higher rutting resistance.

10.4.3.3 Warm-mix asphalt

Ameri, Hesami, and Goli (2013) conducted a laboratory study for using EAF slag as a substitute for natural limestone aggregates in WMA production. EAF slag was used as fine and coarse aggregates in WMA mixtures. The porosity and the roughness of the EAF aggregate are higher than that of the limestone aggregate by scanning electron microscope (SEM) observation. The use of coarse EAF aggregate in WMA mixture enhances Marshall stability, resilient modulus, tensile strength, resistance to moisture damage, and resistance to permanent deformation of the mixture.

10.4.3.4 Slurry seal

Blended limestone and slag aggregate were used in slurry seal (Khan, 1998; Khan & Wahhab, 1998). Mix blend and mix type have a significant effect on the performance of slurry seal. Slag plus limestone produced overall improved results that were better than using limestone or slag separately.

10.4.3.5 Chip seal

The use of chip seals and similar surface treatments have evolved into maintenance treatments that can be successful on both low- and high-volume pavements. The popularity of chip seals is a direct result of their low initial costs in comparison with thin asphalt overlays and other factors that influence treatment selection where the structural capacity of the existing pavement is sufficient to sustain its existing loads (Gransberg, 2005). In many US states steel slag is in their specifications for chip seal aggregates (Li, Shields, Noureldin, & Jiang, 2012).

10.4.3.6 Cold mix-foamed asphalt

EAF steel slag, foundry sand, bottom ash, and reclaimed asphalt pavement (RAP) meeting physical and mechanical properties were mixed in variable proportions that satisfied the technical specifications for cold mixtures. The optimum binder contents was 3%, for both cement and foamed bitumen. The foamed mixtures with 50% EAF slag reached up to 0.73 MPa (mixture integrated with 30% of bottom ash and 10% of RAP) and 0.69 MPa (mixture combined with 30% of foundry sand and 10% of RAP), respectively, in indirect tensile strength (ITS). The foamed mixtures made with EAF slags, foundry sand, bottom ash and RAP, were characterized by low moisture damage in terms of tensile strength and stiffness modulus ratio (SMR), as well as retained creep rate (CR) and secant creep modulus (SCM) and demonstrated a satisfactory durability based on reliable analyses of the creep behavior of the mixes under repeated loading (Pasetto & Baldo, 2012a, 2012b). ASTM D4125 provides standard specification for cold-mixed, cold-l asphalt mixtures (ASTM, 2013b).

Huang and Lin (2011) used coarse BOF slag aggregate with RAP to produce HMA and its use in road construction demonstrated satisfying results.

10.4.3.7 Cold in-place recycling

Slag aggregate has been used in CIR (Son, Al-Qadi, Lippert, & Zehr, 2013), which had the best performance score. Ameri and Behnood (2012) reported that the use of steel slag in CIR can enhance Marshall stability, resilient modulus, tensile strength, resistance to moisture damage, and resistance to permanent deformation of CIR mixes. Use of anionic emulsion is recommended.

10.4.4 Properties and performance of asphalt materials containing slag aggregate

10.4.4.1 Basic Marshall and physical properties

The practices in the 1970s to 1980s showed that BOF slag HMA can be designed in the same way as ordinary HMA mixes, by Marshall method, and presented very high stabilities (1.5–3 times greater than most other asphalt concrete mixes). Resistance to stripping of asphalt cement from the steel slag is 15–25% greater than other HMA mixes. Typical average Marshall characteristics for HMA containing open hearth furnace and BOF slag mixes with the average gradation given are summarized in Tables 10.12, 10.13, and 10.14.

Table 10.12 **Typical gradation for OHF and BOF slag used in HMA**

	Percent passing (%)	
	HMA mixes	
Sieve size, mm	OHF slag	BOF slag
19.0	100	100
12.5	99.9	99.9
9.5	94.4	96.0
4.75	62.2	67.1
2.36	33.2	36.9
1.18	16.5	20.7
0.60	9.0	12.7
0.30	5.8	8.5
0.15	3.4	4.7
0.075	1.1	1.4

Data from Wang, G. C. (1992). The Utilization of Steel Slag in Engineering Applications. PhD Thesis. University of Wollongong, Wollongong, New South Wales, Australia.

Table 10.13 Properties of steel slag asphalt concrete mixes, Marshall designs

Property of laboratory compacted mix	OH slag	BOF slag
Stability (kN)	15.4	16–22
Flow index (mm)	4.3	4.0–5.5
Voids in mineral aggregate (% vol)	20.5	17–20.4
Air voids (% vol)	3.3	3.0–4.0
Asphalt cement content (%, w/w)	6.2	5.5–6.2
Density	2.872	2.869 (2.85–2.90)

Data from Wang, G. C. (1992). The Utilization of Steel Slag in Engineering Applications. PhD Thesis. University of Wollongong, Wollongong, New South Wales, Australia.

Table 10.14 Immersion-Marshall stripping test results

		Striping rating number	
Steel slag	**Retained stability**	**Unstripped**	**Stripped**
OH slag	73.5	3.0	4.0
BOS slag	82.5	3.0	4.0

Data from Wang, G. C. (1992). The Utilization of Steel Slag in Engineering Applications. PhD Thesis. University of Wollongong, Wollongong, New South Wales, Australia.

Numerous technical reports have indicated steel slag HMA provide high rutting resistance, skid resistance, and other good physical properties (Bagampadde et al., 1999; Shatnawi, Abdel-Jaber, Abdel-Jaber, & Ramadan, 2008; Sofilic et al., 2010; Zohrabi & Karami, 2010). Marshall stability of steel slag HMA can generally reach as high as 16,000 N, and average Marshall flow of 2.8 mm (Sorlini, Sanzeni, & Rondi, 2012).

10.4.4.2 Indirect tensile strength

The ITS of HMA containing steel slag exhibited more superior characteristics than those of conventional mixes. Mixes that contained 100% steel slag aggregate had shown better resistance to rutting and to cold temperature cracking (Ali et al., 1992). Highest indirect tensile modulus ITM was obtained for steel slag HMA by Kök and Kuloğlu (2008). Xue et al. (2006) reported that steel slag SMA has high flexural strength compared to basalt aggregate SMA, as 1.64 MPa and 1.52 MPa, respectively. Research by Pasetto and Baldo (2013) showed steel slag HMA (70%) giving positive mechanical performance with ITS at 25°C on dry and wet samples up to 1.27 MPa and 1.07 MPa, respectively.

10.4.4.3 Resilient modulus

The resilient modulus (MR) values of steel slag HMA mixes tend to be some 20% to 80% higher than those of natural aggregate HMA at typical design temperature (29°C). Elastic analysis showed that for the same critical strain levels, thinner steel slag HMA pavement can achieve the same level as the natural aggregate HMA does. Obviously, if thinner steel slag asphalt concrete pavement can be used, this will help to compensate for any high bulk-density disadvantages due to asphalt cement and transportation costs (Emery, 1974, 1976a, 1976b). Amuchi, Abtahi, Koosha, Hejazi, and Sheikhzeinoddin (2013) reported that adding polypropylene (PP) fiber to steel slag asphalt concrete can increase ITS and MR of the steel slag HMA. Amuchi, Abtahi, Koosha, Hejazi, and Sheikhzeinoddin (2013) also reported that steel slag HMA showed increased ITS and MR (2013).

10.4.4.4 Durability

HMA with steel slag used in dense-graded SMA, and fine graded, 9.5−12.5, 19–37.5 mm thickness, air voids 4%, binder 4.5–6, depending on slag content, durability is very good, and friction is superior. HMA with blast furnace slag requires more binder due to high surface absorption, and durability and friction both are very good (Al-Qadi, Son, & Carpenter, 2013). Marshall immersion stability and freeze–thaw splitting test results show that steel slag HMA has good water stability performance, and dynamic stabilities of steel slag HMA mixes are all greater than 1000 time/mm and with excellent high-temperature performance (Li, Sun, & Zhang, 2012).

10.4.4.5 Fatigue behavior

Four-point bending beam fatigue testing was performed in controlled stress mode at various stress levels to characterize the fatigue behavior of the asphalt mixes containing EAF slag. The results showed that the inclusion of EAF in mixes improved fatigue life of samples considerably. This can be explained by the greater adhesion between asphalt cement and slag aggregate (Kavussi & Qazizadeh, 2014; Puy, Jove, Scheibmeir, Abad, & Martinez, 2008).

10.4.4.6 Electrical sensitivity

The electrical sensitivity of BOF slag HMA was investigated in accordance with ASTM D257 and it was demonstrated that the electrical conductivity of steel slag mixtures were better than that of limestone mixtures (Ahmedzade & Sengoz, 2009).

10.4.4.7 High-temperature stability and low-temperature crack resistance

The test analysis results prove that the high-temperature stability, low-temperature crack resistance, and fatigue property of the bituminous mixture with all steel slag as aggregate or partial steel slag as aggregate are superior to those of macadam mixture (Lu & Li, 2012; Ziari & Khabiri, 2007).

10.4.4.8 Volumetric stability and expansion issues

Stockpiling and aging are the basic treatment techniques for steel slag use in asphalt paving. Rohde, Nŭñez, and Ceratti (2003) reported that steel slag must be stocked in the open air for at least 4 months before it can be used in pavement construction. However, stockpiling times are varied based on each specific slag and experience. Users must determine the sufficient time for aging based on thorough testing and examination.

Steel slag HMA has been used in Ontario, Canada, on major highways since the late 1970s. In 1992, their use was discontinued because of premature pavement deterioration (Afrani, Bradbury, & Hajek, 1995; Hajek & Bradbury, 1995). Research was conducted to investigate the causes (Farrand & Emery, 1995) and concluded that steel slag of suitable quality and consistency can be used to produce good aggregate for use in HMA; volume expansion of the steel slag aggregate is a problem that must be controlled before the aggregate can be used in HMA; steelmaking flux and slag practices must be compatible with making low-volume expansion slag aggregate; performance-based testing should be used to measure the volume expansion of the steel slag aggregate; and total quality management is necessary to cover all aspects of steel slag aggregate production to ensure an aggregate of suitable quality is delivered to the end user. Canadian SHRP (C-SHRP) developed Bayesian statistical analysis approach as a consequence of the premature pavement deterioration of slag HMA, which provides an independent review and endorsement of prediction models by experts, and it facilitates quantification of the influence and contribution of field data and expert judgment in the modeling process.

10.5 Research, development, and trends in slag use in asphalt paving

10.5.1 Slag asphalt absorption

High asphalt absorption of slag has been a main obstacle to hinder the utilization of slag in HMA. Chen et al. (2013, 2014) indicated that in asphalt absorption of steel slag (AAOS), the weight of asphalt absorbed by 100 g steel slag is much higher than for limestone or basalt; AAOS increases slowly with the prolongation of storage time or the increase of storage temperature; and the increase of viscosity causes a drastic reduction of asphalt absorption.

Amuchi, Abtahi, Koosha, Hejazi, and Sheikhzeinoddin (2013) reported that to increase the viscosity of the bitumen and/or to decrease the effective surface of slag aggregates by using PP fibers can reduce the steel slag absorption. A PP fiber-reinforced steel slag asphalt concrete is proposed. The treatment with 2% of 19 mm PP fibers experiences a decrease in optimized asphalt content about 15% in comparison with the neat mixture. Moreover, ITS and MR have increased.

Gneiss coarse aggregate and steel slag fine aggregate were used in HMA, which presented lower asphalt absorption than original mixes (Chen, Wu, Wen, Zhao, Yi, & Wan, 2015).

10.5.2 Expansion

Tank-type hot disintegrating and rotary cylinder technology processing have been developed to treat steel slag (Liao, Zhang, Ju, & Zhao, 2013).

10.5.3 Reclaimed asphalt pavement containing slag aggregate

Recent research found that some steel slag aggregates in RAP, with 92% steel slag aggregates, showed considerably high expansion potential, up to 6.2% swell. The overall

RAP gave maximum expansion amounts of 1.69% and 1.46%, respectively, which indicates lower tendencies to expand than virgin steel slag aggregates (Deniz, Tutumluer, & Popovics, 2010). HMA with RAP and virgin slag aggregate will provide increased friction (hence increased strength) to the HMA mixes (Widger, Skilnick, & Zabolotnii, 2012). The usability and recyclability are to be further studied.

10.5.4 Life cycle cost analysis and recyclability

Recycling of pavements and using by-product in pavement construction represents an important opportunity to save on mining and the use of virgin materials, conserve energy, divert materials away from landfills, and save scarce tax dollars. How much pollution, energy, natural resources, and money could be saved by using secondary materials in road construction? What are the engineering limits of using recycled materials in roads? Can we recycle over and over again pavements that contain slag aggregates? Quantified research will be needed (Horvath, 2003).

10.5.5 Quieter pavement

13.2 mm and 16 mm steel slag aggregate was used to replace granite aggregates in the construction of a porous pavement surface course. From the results obtained from field monitoring tests, it was observed that the new asphalt mixes provided better reduction in tire–pavement noise as compared with the other types of asphalt mix currently used in Singapore (Fang, Chong, Nyunt, & Loi, 2013).

10.5.6 Abrasion dust of slag HMA pavement

Fine abrasion dust particles originated from slag asphalt concrete and its size dependency was investigated. There was no enrichment in abrasion dust particles with diameter less than 75 μm, which suggests that environmental risks of abrasion dust of slag asphalt pavement are yet to be addressed (Takahashia, Shimaoka, Gardner, & Kida, 2011).

10.5.7 Thin HMA overlays high friction surface treatment

Steel slag has become one of the major sources of aggregates for highway pavement constructions in many state Departments of Transportations (DOTs) in the United States. In the past decades, the use of steel slag in HMA pavements has proven to be extremely successful nationwide. In particular, steel slag is one of the superior aggregates for constructing smart HMA pavements for heavy truck traffic, including SMA and thin, and ultra-thin, HMA overlays, due to its unique physical and mechanical properties, such as hardness, durability, and surface texture. Another potential use for steel slag is for high friction surface treatments (HFST) that are increasingly catching the attention of pavement engineers as an effective solution to addressing high friction demand on horizontal curves. Although steel slag does not have a PSV similar to that of calcined bauxite, its local availability and low price make it a viable aggregate source for HFST, particularly for less severe geometric conditions or relatively large scale projects (Li, 2016).

In Fig. 10.7 a 19 mm thick 4.75 mm dense-graded HMA pavement has been placed on an interstate highway. The aggregate is compromised of 39% steel slag by weight. The pavement has performed satisfactorily with reference to surface friction and ride quality. Fig. 10.8 shows HFST test patches of steel slag lying on a multilane highway. The test patches are composed of a layer of 1–3 mm steel slag bonded to the existing pavement surface using a specialized resin binder. These test patches functioned very well in terms of surface friction and texture after one winter maintenance season.

Fig. 10.7 Thin 4.75 mm dense-graded HMA overlay.

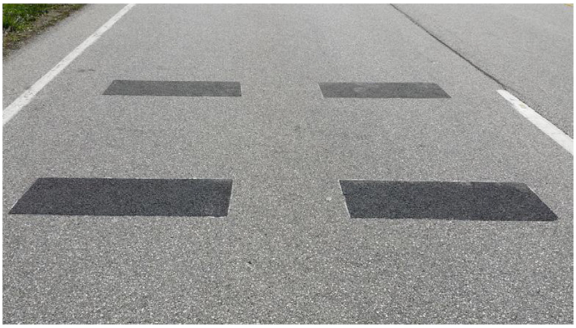

Fig. 10.8 HFST test patches with steel slag.

10.5.8 Blending use of steel slag with recycled concrete aggregate and fly ash

Anastasiou, Filikas, and Stefanidou (2014) used construction and demolition waste (CDW) as fine aggregate, EAF slag as coarse aggregate, and high calcium fly ash (HCFA) as supplementary cementitious material to make concrete. The results showed that the combination of CDW with EAF slag made excellent aggregates for concrete that partially recovered strength loss due to fine CDW and improved the concrete microstructure by providing good aggregate-binder bonding.

Chen et al. (2015) used coarse gneiss as coarse aggregate and fine weathered fine BOF slag aggregate (weathering treatment for 12 months) in HMA. The results showed that the HMA performed good in deformation resistance, crack and moisture resistance, and lower asphalt binder content was required.

10.6 Summary

Current pavement structure design guidance and asphalt material mix design guidance covering the basic requirements for materials and performance for the end products can be used for asphalt paving applications involving slag aggregates. There is always room to improve to reflect the recent development of slag use in asphalt paving practices to include a wider variety of slags and beyond the areas of production. Specifications dealing with slag aggregates should covering special features to ensure satisfactory performance such as uniformity, deleterious materials, unit weight, and potential expansion.

Use of slag in asphaltic mixes is still highly localized in steel production areas. Some agencies do not permit its use, although the performance record of steel slag mixtures is reported to be excellent. Some inputs should be considered in further evaluation of steel slag asphaltic mixtures. This process may lead to the development of technical specifications and recommendations for more extensive use of steel slag aggregates in pavement construction.

With the endeavors of producers, users, researchers, and policy makers, slag aggregate will continue to make a positive contribution to high-quality HMA, pavement surface treatment, and asphalt pavement recycling technology in areas of its production and beyond.

Questions

10.1 What are the Superpave consensus properties of aggregate for asphalt mixes?
10.2 What are the Superpave source properties of aggregate for asphalt mixes?
10.3 What are Marshall stability and flow?
10.4 Asphalt paving involves which major steps?
10.5 What are the major features of steel slag HMA?
10.6 Why does steel slag HMA have better rutting resistance compared to some natural aggregate HMA?
10.7 List two surface treatment techniques.
10.8 Explain “stripping” in HMA mixes?

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Slag use as an aggregate in concrete and cement-based materials

11

11.1 Introduction

Concrete is the most prevalent construction material used in infrastructure construction due to its widespread availability, cost effectiveness, structure characteristics, and ability to be molded into limitless geometries. Aggregate, which makes up approximately 65–85% of concrete mixture, is an important ingredient in concrete and plays a very important role in concrete properties and durability.

Aggregate properties for Portland cement concrete (PCC) are in many aspects different from aggregates used for base courses or hot-mix asphalt (HMA). For example, aggregate gradation becomes a key factor as it controls the workability of the plastic concrete. Further, the aggregates used in concrete are a blend of fine and coarse aggregates to achieve an economical mix. Coarse aggregate is defined as aggregate predominantly retained on the 4.75 mm (No. 4) sieve or that portion of an aggregate retained on the 4.75 mm sieve. Fine aggregate (FA) is defined as aggregate passing a 9.5 mm (3/8 in.) sieve and almost entirely passing a 4.75 mm sieve, and predominantly retained on the 75 μm (No. 200) sieve. In fine aggregate, fineness modulus is used to denote the relative fineness of the sand, which is defined as one-hundredth of the sum of the cumulative percentages held on the standard sieves in a sieve test of sand. Six sieves are used in the determination, 4.76, 2.38, 1.19, 0.595, 0.297, and 0.149 mm (Nos. 4, 8, 16, 30, 50, and 100) sieves. The smaller the value of the fineness modulus, the finer the sand. The fineness modulus for a good sand should range between 2.25 and 3.25 (ASTM, 2009).

In making ordinary PCC, the strength of the aggregate is not as important as it would be when used as a granular base course material. The aggregate in ordinary concrete acts as a filler so that not as much cement paste is needed. Bond strength between aggregate and cement paste is more important than aggregate itself in concrete. Research has found that normal concrete failure is mainly a result of failure of the bonding between aggregate and cement paste. As discussed in this chapter, concrete using steel slag aggregate presents a different situation. The shape and surface texture features of aggregate have significant influence on the bonding and, therefore, the compressive and tensile strength of the concrete. In most cases the mechanical bond can be improved by an aggregate with a rough surface texture, and chemical bond can be improved if the aggregate has certain chemical activity with cement.

Much research was conducted in the last century after concrete became a major construction material. However, it has not been clearly and quantitatively recognized how aggregate affects the strength of concrete and other properties. The difficulties come from three areas: (i) lack of an effective test method to test the bond strength between

The Utilization of Slag in Civil Infrastructure Construction. http://dx.doi.org/10.1016/B978-0-08-100381-7.00011-2

aggregate and hardened cement paste (HCP), and to distinguish the contributions of mechanical and chemical bonding; (ii) lack of a statistical physical parameter(s) to describe comprehensively the geometric shape, particle size, distribution of partial size, and surface texture of aggregate; and (iii) the structural sensitive property of concrete. Even though much research has revealed some basic and important findings, the research has found that among the three structural units of phases—the matrix phase (cement paste), the dispersed phase (aggregate), and the interface phase (interface between matrix and dispersed phase)—the latter is the weakest link (Hsu & Slate, 1963). Research also showed that using hydraulic active aggregate can increase the chemical bond strength.

The properties of aggregate, including geometric shape, surface texture, chemical activity, and hydrophilicity have significant influence on bonding strength. Fig. 11.1 illustrates the effects from 10 different scenarios including aggregate shape, surface texture, and disrupt position (Zhou, 1985). If the bond between aggregate and cement paste or mortar in case (A) is regarded as 1; other scenarios are given in Fig. 11.1 where the highest strength can doubled. It can be seen that aggregate particles with rough surfaces have higher bond strength. Compactness of the interface can be enhanced by improving the affinity of aggregate for moisture.

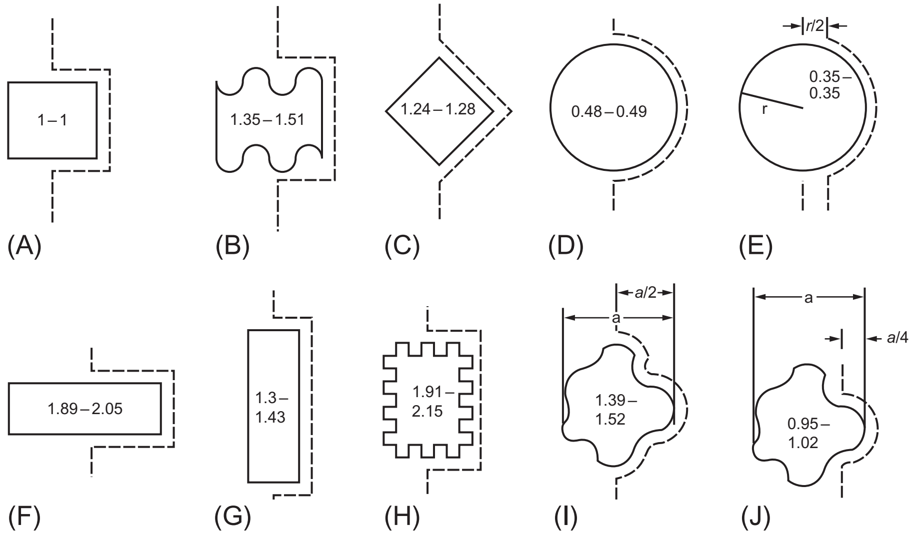

Fig. 11.1 The effects of aggregate shape, surface texture, and disrupt position on concrete. (A) Cubical, with three sides of smooth surface. (B) Cubical, with two sides of rough texture. (C) Cubical, with two sides of smooth surface. (D) Spherical, half of the smooth surface. (E) Spherical, covered the surface of 1/4 of the diameter. (F) Rectangular, horizontal postilion, with three sides of smooth surface. (G) Rectangular, vertical position, with three sides of smooth surface. (H) Cubical rough surface, covered half of the surface. (I) Angular surface, covered half of the surface. (J) Angular surface, covered the surface of 1/4 of the diameter.

It is well known that in concrete, the bond strength between aggregate and HCP (interface between HCP and inert natural mineral aggregate) is the weakest link in the composite. The normal methods to improve bond include the use of aggregates with rough surfaces and porous structure, or the addition of superfine chemically active mineral additives, such as silica fume, pumice, and zeolite. These methods are intended to consolidate the interface bond physically and chemically. Steel slag inherently possesses both of these advantages in terms of physical and chemical strengthening. Additionally, compared with natural inert mineral aggregate, steel slag aggregate can react chemically with HCP/mineral additive to some extent.

In most ordinary concrete mixtures with moderate strength, the strength of aggregate can be minimal because the compressive strength of the concrete is controlled by the bond strength. However, for concrete using slag aggregate (eg, steel slag) the situation will be different. Steel slag processes hydraulic activity, with rough surface and porous texture that increase both the mechanical and chemical bond between the cement paste and steel slag aggregate. It is necessary to investigate and compare the strength of the three phases (ie, matrix, aggregate, and the interface of slag aggregate and inert natural aggregate), which will be presented in this chapter.

Aggregate particle shape also influences the workability of the concrete mix. Angular aggregates require more mortar to fill voids and separate aggregate particles for workability, which results in a higher water–cement ratio for a given cement factor and consistency. Super plasticizer may be used for crushed aggregates and high-performance concrete.

Aggregate soundness and the bonding with cement mortar can influence concrete durability such as freezing and thawing. If the aggregate is unsound, major distress may result in concrete structure, such as pitting and popouts, D-line cracking deterioration, and map cracking. Several natural aggregates can cause deterioration of concrete, including chert, limestone, and shale. Use of manufactured and slag aggregates as supplements and replacements for conventional aggregates in concreting is one of the effective ways to improve concrete durability.

Testing specifications and procedures for concrete must be used and met when using slag aggregates in concrete. The relevant ASTM and AASHTO specifications are shown as follows:

ASTM C666 (resistance of concrete to rapid freezing and thawing). The purpose of this specification is to determine how concrete will react under continuous cycles of freezing and thawing and to rank aggregates.

ASTM 0215 (fundamental transverse, longitudinal, and torsional frequencies of concrete specimens). The purpose of this test is to determine the relationship between strength loss and cycles of freezing and thawing. Test specimens are made in accordance with ASTM C192 (making and curing concrete test specimens in the laboratory).

ASTM 0597 (pulse velocity through concrete). The major purpose of this specification is to check the uniformity in mass concrete, to indicate characteristic changes in concrete, and in the survey of field structures estimate the severity of deterioration, cracking, or both.

ASTM 0123 (lightweight pieces in aggregates). The purpose of this specification is to determine the approximate percentage of lightweight pieces in aggregates by means of sink-float separation in a heavy liquid of suitable specific gravity.

ASTM 0289 (potential reactivity of aggregates, chemical method). The purpose of this test procedure is to determine the potential reactivity of an aggregate with alkalies in PCC in a very short time. This is a test for the alkali–silica reaction and is not intended for the alkali–carbonate reaction.

ASTM 0117 (materials finer than 75 μm (No. 200) sieve in mineral aggregates by washing). The purpose of this test is to determine the amount of material finer than a No. 200 (75 μm) sieve in aggregate by washing. Clay particles and other aggregate particles that are dispersed by the wash water as well as water-soluble materials will also be removed from the aggregate during the test.

ASTM C142 (clay lumps and friable particles in aggregates). The purpose of this specification is to measure only particles that might cause unsightly blemishes in concrete surfaces. It is an approximate method for the determination of clay lumps and friable particles in natural aggregates.

ASTM C33 (concrete aggregates). The purpose of this specification is to ensure that satisfactory materials are used in concrete. The specification covers both fine and coarse aggregates but does not cover lightweight aggregates. The specification establishes definitions for fine and coarse aggregate and places restrictions on grading, deleterious substances, and soundness. The specification also establishes methods for testing and sampling. This specification lays down the fundamental rules for fine and coarse aggregates used in concrete as well as the sampling and testing methods to be followed.

ASTM C682 (evaluation of frost resistance of coarse aggregates in air-entrained concrete by critical dilation procedure). The purpose of this procedure is to evaluate the frost resistance of coarse aggregates in air-entrained concrete. This procedure is basically the same as that for the preceding specification.

ASTM C40 (organic impurities in sands for concrete). This specification covers an approximate determination of the presence of injurious organic compounds in natural sands that are to be used in cement mortar or concrete. The principal value of the test is to furnish a warning that further tests of the sands are necessary before they are approved for use.

ASTM C227 (potential alkali reactivity of cement-aggregate combinations, mortar-bar method). The purpose of this specification is to determine if an aggregate will react with the alkalies in the cement. This test is basically to predict the alkali–silica reaction.

AASHTO M80-13 (standard specification for coarse aggregate for hydraulic cement concrete). This specification covers coarse aggregate, other than lightweight aggregate, for use in concrete. Several classes and gradings of coarse aggregate are described in this specification.

Slag aggregate can be incorporated in concrete to facilitate several benefits including the modification and improvement of material properties. Blast furnace slag has been widely used or permitted to be used in concretes for many years, both as a cementing medium and aggregate (Dean, 2005; Dunster, 2002; Fonseca & Gomes, 2010; Motz, 2002; Nakagawa, 2007). Air-cooled blast furnace slag (ACBFS) is a by-product of iron manufacturing, in which silica and alumina constituents combine with lime to form a molten slag that collects on top of the iron in a blast furnace. If this molten slag is allowed to cool slowly it solidifies to a gray, crystalline, stone-like material, known as air-cooled slag. This by-product is then crushed and screened for sizes suitable as coarse aggregate.

Some authors present the results for the evaluation of the application of ground blast furnace slag as fine aggregate, concluding that, with some granulometric adjustments, this slag can be used as fine aggregate in mortars and concretes. Nevertheless, the rugosity of slag aggregates and the absence of fine grains demand the development of specific dosage and application technologies.

The application of steel slag as an aggregate in cement concrete has previously been considered a forbidden zone since a failure of the structures (Crawford, 1969). In the last couple of decades, especially recent years, research into this use has been carried out. In Japan, several patents have been taken out regarding the use of steel slag to replace crushed stone or sand as coarse and fine aggregate in cement concrete (Japanese Patent, 1982a,1982b). The potential use of steel slag as an aggregate in concrete or other rigid matrices has been investigated by many researchers (Abu-Eishah, El-Dieb, & Bedir, 2012; Anastasiou, Filikas, & Stefanidou, 2014; George & Sorrentino, 1982; Kawamura, Torii, Hasaba, Nicho, & Oda, 1983; Maslehuddin, Sharif, Shameem, Ibrahim, & Barry, 2003; Montgomery & Wang, 1990, 1991, 1992a, 1992b; Pacheco, Etxeberria, Meneses, Berridi, & Avila, 2010; Wang, 1988, 1992). The major concerns over its use in concrete being associated with volume stability arising from the effects of f-CaO and periclase.

Several processes have been developed for slag treatment. Generally these processes are utilized to provide cooling and limited crushing of the molten slag. They range in technique from the extensive use of high-pressure water, steam, or air to provide cracking and, in some cases granulation, to the dry process, which utilizes natural cracking on solidification of thin layers of the hot slag by water sprinkling.

It has been established that the use of steel slag contributes to the ultimate strength of concrete (Zaki, Metwally, & El-Betar, 2011). A microhardness test may be employed to measure individual microstructures within a larger matrix, or to measure the hardness gradients of a part along the cross section. Thus determined, the microhardness correlates with the strength of the material tested. Du, Wang, Lin, Liu, and Liu (2010) used a microhardness test along the interfacial transition zone (ITZ) of recycled aggregate concrete to find the correlation with the strength of the concrete. Another test that correlates closely with the strength of the material is the bond strength test. The bonding between steel slag aggregate and cement paste determines the strength of the concrete. A detailed, microlevel analysis exploring how steel slag contributes to the additional strength of the concrete was undertaken using microhardness and the bond strength test with the process and findings documented in this chapter.

As has been demonstrated, the use of steel slag can be generally divided into four areas, in keeping with the increase in the use of the potential chemical energy of steel slag from nil to full, the requirement relating to the stability of the steel slag being from lenient to rigorous, due to the expansion property of the steel slag. This suggests that in applications where more potential chemical energy is utilized, a higher degree of stability in the steel slag is required and more quantitative work is needed.

The use of steel slag to replace natural aggregate in concrete is initially based on the consideration of availability of natural resources and the good characteristics of steel slag. In nature, the resources of natural mineral aggregates of high engineering quality that can be used ultimately will become exhausted (Collins, 1976). In Japan, the proportion of natural mineral aggregates in concrete diminishes year by year and is being replaced by artificial aggregates and industrial by-product aggregates (Ayano & Sakata, 2000; Japanese Civil Engineering Society, 1980). Shortages of high-quality natural aggregates have been experienced in a number of areas of the United States (Lewis, 1982). It was once estimated that after the year 2010 the global concrete industry will annually required 8–12 billion tonnes of natural aggregate. The production of crushed stone has increased at an average annual rate of about 3.3% in the United States for the past 25 years (Fronek, Bosela, & Delatte, 2012).

On the other hand, steel slag possesses good physical properties that can be utilized to provide strength when used as an aggregate in concrete.

11.2 Mechanical behavior of concrete containing steel slag aggregate

The mechanical behavior of concretes containing steel slag as aggregate were studied and the results are presented in this section. The mechanical behavior include strength-related, fracture-related, brittleness, and fracture toughness properties, followed by microlevel examination to explain the mechanism on the modified mechanical properties compared to ordinary concrete. A laboratory study assured that steel slag possesses good physical and mechanical properties and has sufficient stability for use as a coarse aggregate in Portland concrete.

11.2.1 Strength-related properties

A laboratory study program was established to investigate the mechanical properties of steel slag concrete in which the steel slag has been processed in a particular manner to produce instant chilled (or shallow box chilling) steel slag. The instant chilling process is presented in Section 5.4.2.7.

11.2.1.1 Materials

Cement: Type I ordinary Portland cement.

Aggregate: Coarse aggregates used include crushed limestone and instant chilled basic oxygen furnace (BOF) slag. The properties of the steel slag are presented in Tables 11.1–11.3. Free lime content of the steel slag was <4%. MgO existed as mixed

Table 11.1 Properties of the steel slag used

Properties	Steel slag	Limestone
Aggregate crushing value (%)	4.8	8.7
Water absorption (%)	2.5	2.3
Free water content (%)	1.4	1.1
Specific gravity	3.61	2.54
Unit weight (uncompacted, kg/m^3)	1680	1350

Table 11.2 Grading of steel slag

Sieve size (mm)	20	15	10	5	2.5
% Passing	100	90.5	38.7	1.6	1.6

Table 11.3 Chemical composition

SiO_2	Al_2O_3	T Fe	CaO	MgO	P_2O_5	f-CaO	Alkalinity (B)
18.9	1.7	22.4	43.3	8.4	1.0	3.8	2.17

Alkalinity $B = CaO/(SiO_2\% + P_2O_5\%)$.

crystals in solid solution (RO) phase. No periclase existed in the slag. The fine aggregate was a medium sand. Common tap water was used in all mixes.

The instant chilled steel slag (ICSS) has sufficient stability to be used as aggregate in concrete. Hydrothermal breakdown (powdering ratio) of the slag is very low (<0.5%) after 8h at 100°C test (refer to Section 5.2.2 for the powdering ratio test). Even under severe conditions of autoclaving (175°C, 8 atm), the powdering ratio is <1.5%.

Concrete mixes with a constant water-to-cement (W/C) ratio (0.5) were made in which the slag contents as a percentage of total coarse aggregate were varied from 0% to 100%. Mix proportions are shown in Table 11.4.

Table 11.4 **Mix proportions for concrete tests**

		Materials used by weight (kg/m³)				Mix ratio	Slag	
Mix no.	**W/C**	**Cement**	**Sand**	**Crushed limestone**	**Slag**	**C:S:CL:slag**	**By volume (%)**	**By weight (%)**
1–0	0.5	420	620	1150	0	1:1.48:2.74:0.00	0	0
1–2	0.5	420	620	920	286	1:1.48:2.19:0.68	20	24
1–4	0.5	420	620	690	572	1:1.48:1.64:1.36	40	45
1–6	0.5	420	620	460	859	1:1.48:1.10:2.04	60	65
1–8	0.5	420	620	230	1145	1:1.48:0.55:2.73	80	83
1–10	0.5	420	620	0	1431	1:1.48:0.00:3.40	100	100

11.2.1.2 Strength and elastic modulus

The experimental results of strength and elastic modulus-related tests on various specimen geometries are shown in Figs. 11.2–11.5.

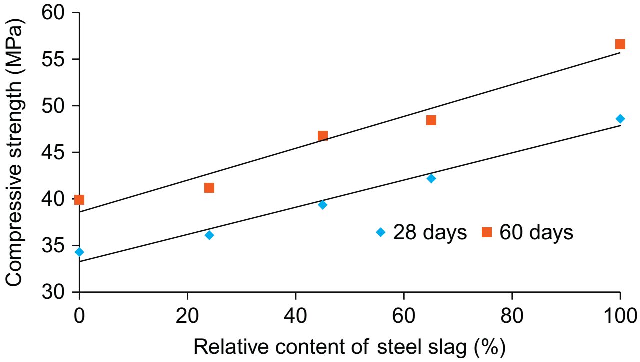

Fig. 11.2 Compressive strength vs. steel slag coarse aggregate content.

From Fig. 11.2 it can be seen that the comprehensive strength of the concrete specimens increases linearly with increase in slag content for specimens tested at 28 and 60 days.

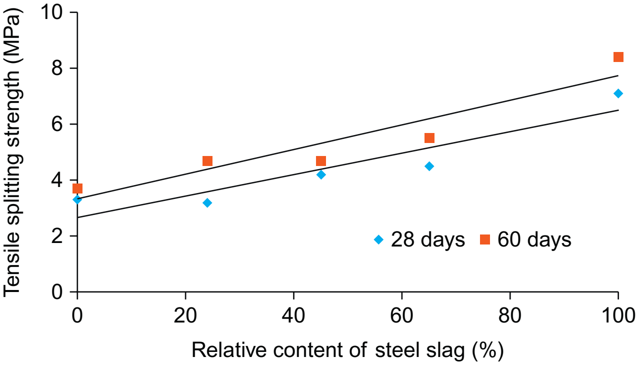

Fig. 11.3 Tensile splitting strength vs. steel slag coarse aggregate content.

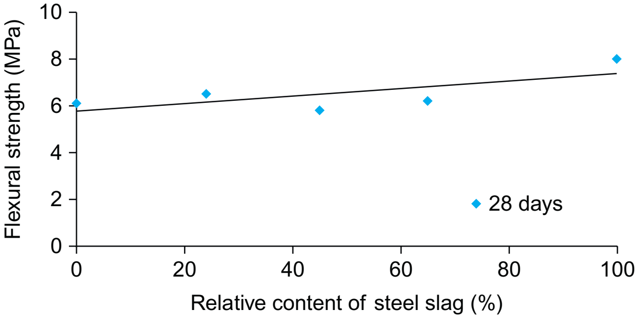

Fig. 11.4 Flexural strength vs. steel slag coarse aggregate content.

Tensile splitting strength, Fig. 11.3, increases with the increase in slag content with the most significant improvement occurring at high slag replacement levels. Flexural strength, Fig. 11.4, remains essentially constant at slag replacement levels up to 65% with considerable increase occurring at higher values of slag content. As shown in Fig. 11.5, modulus of elasticity exhibits similar trends to those of compressive strength.

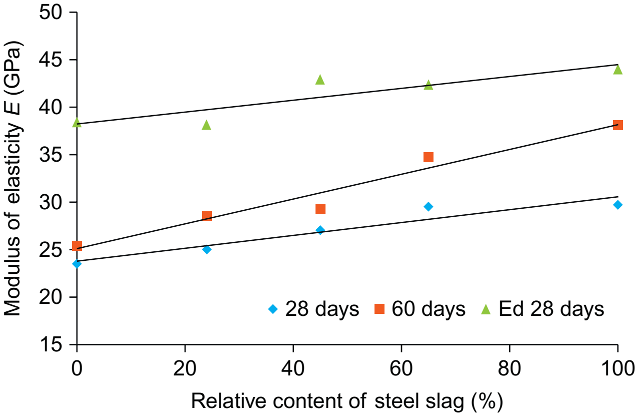

Fig. 11.5 Modulus of elasticity vs. steel slag coarse aggregate content.

It can be seen in Section 11.2.3, examination of the fracture surfaces of the concrete cubes after tensile splitting indicated that, as the steel slag content is increased, there is a significant decrease in interfacial fracture between the aggregate particles and the mortar, with the steel slag showing no tendency to debond from the matrix. This indicated that the interfacial bond is improved, resulting in a general increase in strength of the concrete with high slag content.

Compressive strength, tensile splitting strength, flexure strength, and modulus of elasticity all increase in value with increase in relative content of the steel slag coarse aggregate. Concrete mixes containing BOF slag as total coarse aggregate content exhibit increases of 45% and 120%, for compressive and tensile splitting strengths respectively, over those containing limestone as total aggregate content.

Similar research was conducted by Barišic, Dimter, and Rukavina (2014). It was found that the compressive and indirect tensile strength of the concrete increased with curing age. The strength of mixes with low cement contents increased with the slag content, while that of mixes with higher cement contents decreased with slag content. Finally, the average indirect tensile strength for all mixes as a percentage of compressive strength was 14%.

Beshr, Almusallam, and Maslehuddin (2003) reported that the highest and lowest compressive strength were obtained in the concrete specimens prepared with steel slag and calcareous limestone aggregates, respectively. Similarly, the split tensile strength of steel slag aggregate concrete was the highest.

11.2.2 Fracture-related properties

The composing concrete materials as described in Section 11.2.1 were used for fracture-related study, which includes brittleness, specific brittleness, and fracture toughness.

Brittleness. Brittleness of the steel slag concrete was determined by longitudinal compressive testing of 100×100×300mm prismatic specimens. Cross experiment design formed the basis of a series of 16 mixes covering three variable parameters, being water/cement ratio, slag content, and cement content. Four values of water/cement ratio were fixed (0.48, 0.56, 0.64, 0.71) and four target values of cement content (260, 310, 370, 420 kg/m^3) and slag content (1360, 1400, 1440, 1480 kg/m^3) were selected. It became necessary to adjust cement and slag content to obtain normal yield concrete mixes.

Details of mix constituents and final, adjusted proportions for the slag concretes are presented in Table 11.5.

For comparison, companion specimens of concretes containing limestone aggregate were designed, manufactured, and tested in a similar manner. Mix constituents and proportions are given in Table 11.6.

Specimens were uniaxially loaded in compression to ultimate and subsequently unloaded in a stiff testing machine, applied load and corresponding axial deflection being continuously recorded by an Instron universal testing machine. Load-deformation plots similar to that schematically represented in Fig. 11.6 were obtained.

Brittleness index *B* was calculated as the ratio of the area of elastic recovery (elastic deformation energy) to that of the nonelastic portion (irreversible deformation energy) corresponding to the peak point of the σ–ε curve (ie, B = area II/area I). *Specific brittleness* (defined as brittleness per unit strength) was computed for each specimen by dividing brittleness index *B* by the corresponding value of maximum compressive strength, σ_c.

Table 11.5 Mix proportions for brittleness of steel slag aggregate concretes

Mix no.	Materials used by weight (kg/m^3)				Mix ratio
	Cement	Sand	Steel slag	W/C	C:S:slag
SB 1	358	831	1353	0.48	1:2.32:3.78
SB 2	253	883	1440	0.64	1:3.49:5.69
SB 3	336	822	1344	0.56	1:2.45:4.00
SB 4	259	855	1393	0.71	1:3.30:5.38
SB 5	270	918	1496	0.48	1:3.40:5.54
SB 6	346	779	1273	0.64	1:2.25:3.68
SB 7	276	886	1443	0.56	1:3.21:5.23
SB 8	325	776	1264	0.71	1:2.39:3.89
SB 9	399	794	1293	0.48	1:1.99:3.24
SB 10	294	837	1367	0.64	1:2.85:4.65
SB 11	372	782	1276	0.56	1:2.10:3.43
SB 12	300	807	1317	0.71	1:2.69:4.39
SB 13	303	887	1445	0.48	1:2.93:4.77
SB 14	368	751	1225	0.64	1:2.04:3.33
SB 15	307	852	1388	0.56	1:2.78:4.52
SB 16	347	750	1221	0.71	1:2.16:3.52

Table 11.6 Mix proportions for brittleness of limestone aggregate concretes

Mix no.	Materials used by weight (kg/m^3)				Mix ratio
	Cement	Sand	Limestone	W/C	C:S:LS
LB 1	250	634	1346	0.68	1:2.54:5.38
LB 2	340	605	1285	0.50	1:1.78:3.78
LB 3	378	593	1260	0.45	1:1.57:3.33
LB 4	420	579	1234	0.40	1:1.38:2.94

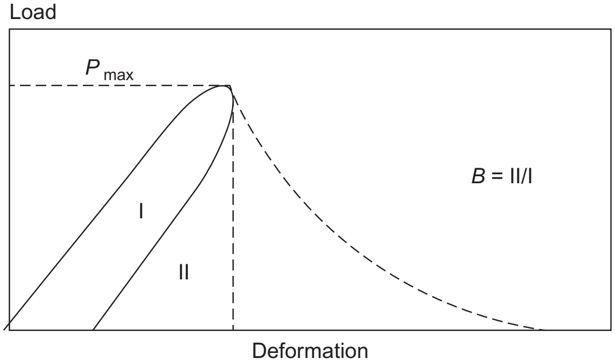

Fig. 11.6 Typical load-deformation plot to determine brittleness index *B*.

Fracture toughness. Fracture toughness was determined using compact compression specimens consisting of steel slag aggregate concrete and crushed limestone aggregate concrete (Barr, Hasso, & Sabir, 1985; Bear & Barr, 1977). Details of specimen dimensions and method of loading for this study are given in Fig. 11.7. Mix specifications are shown in Table 11.7.

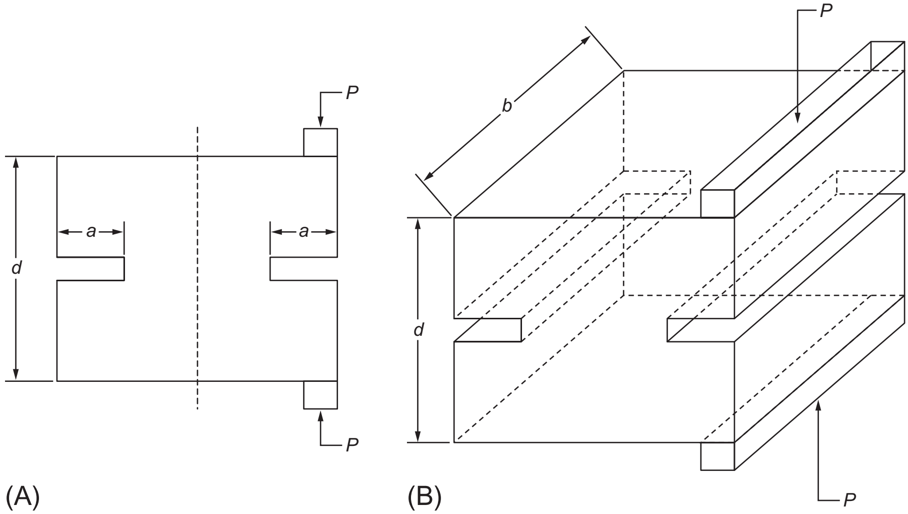

Fig. 11.7 Compact compression specimen for determination of fracture toughness. (A) Front view of the specimens. (B) Three-dimensional view of the specimen.

Table 11.7 **Mix proportions for fracture toughness tests using compact compression specimens**

Mix no.	Materials used by weight (kg/m³)					Mix ratio
	Cement	Sand	Steel slag	Limestone	W/C	C:S:slag or stone
SF 1	325	776	1264	–	0.71	1:2.39:3.89
SF 2	253	883	1440	–	0.64	1:3.49:5.69
SF 3	270	918	1496	–	0.48	1:3.40:5.54
SF 4	372	782	1276	–	0.56	1:2.10:3.43
SF 5	399	794	1293	–	0.48	1:1.99:3.24
LF 1	428	582	–	1180	0.44	1:1.36:2.76
LF 2	420	620	–	1150	0.50	1:1.48:2.74
LF 3	356	609	–	1250	0.52	1:1.71:3.51

11.2.2.1 Results of brittleness and fracture toughness

Brittleness

The results from the brittleness tests at the age of 28 days on steel slag aggregate concrete and limestone aggregate concrete are presented in Fig. 11.8.

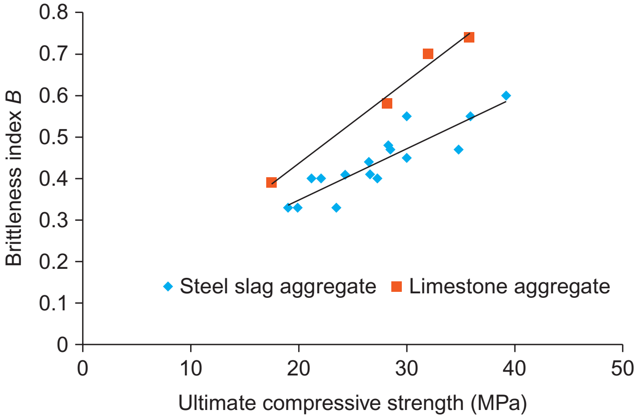

Fig. 11.8 Relationship between brittleness index and compressive strength.

Two significant trends are exhibited. First, for corresponding values of compressive strength, the brittleness index of steel slag concrete is considerably less than that of limestone aggregate concrete. Second, the slope of the linear equation for the steel slag aggregate concretes is less than that for limestone aggregate concretes. This has ramifications in that, for higher values of compressive strength, steel slag aggregate concrete can be expected to exhibit much lower degrees of brittleness than limestone aggregate concrete.

Fig. 11.9 shows plots of specific brittleness versus compressive strength for both types of concrete. It can be observed that, for steel slag aggregate concrete, there is a definite trend for the specific brittleness to decrease as compressive strength increases, whereas for limestone aggregate concrete, no well-defined change in specific brittleness occurs with compressive strength.

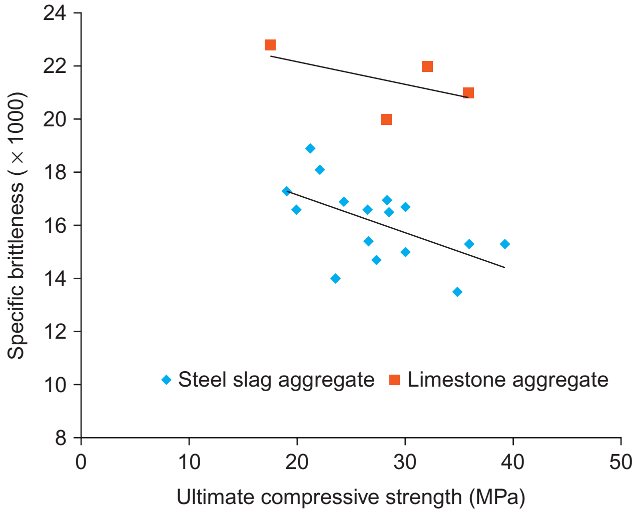

Fig. 11.9 Relationship between specific brittleness and compressive strength.

Fracture toughness

For the compact compression specimen shown in Fig. 11.6 the value of stress intensity factor K_{IC} is given by the relationship:

$$K_{IC} = \frac{P}{bd^{1/2}}\left[18.3(a/d)^{1/2} - 430(a/d)^{3/2} + 3445(a/d)^{5/2} - 11076(a/d)^{7/2} + 12967(a/d)^{9/2}\right] \tag{11.1}$$

where P is the ultimate load (N); bd are the specimen width and depth (mm); and a is the length of the slot (mm).

In the specimen used for the tests, $bd = 100$ mm, $a = 30$ mm. The specimens were loaded in eccentric compression through two mild steel bars of 6 mm square cross section and 100 mm length.

The compact compression test results at ages of 28 days for steel slag aggregate concrete and limestone aggregate concrete are presented in Fig. 11.10.

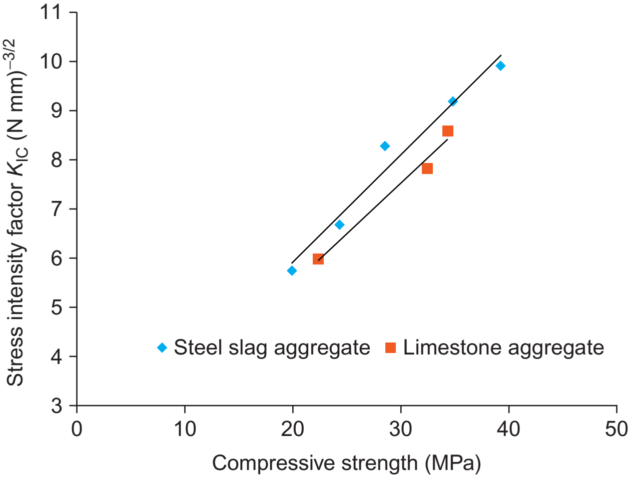

Fig. 11.10 Relationship between stress intensity factor and compressive strength.

It can be observed from Fig. 11.10 that fracture toughness, as measured by the stress intensity factor K_{IC}, increases with increasing compressive strength for both slag concretes and limestone concretes, with higher values, of the order 10%, being obtained for the steel slag aggregate concrete.

From the series of results, considerable benefits can be derived from the use of ICSS as coarse aggregates in concrete. In addition to improved strength properties found in Section 11.2.1, such as compressive, tensile, flexural strength, and modulus of elasticity, reduction in brittleness and increase in fracture toughness can be obtained.

The brittleness index of concretes containing steel slag aggregate is considerably less than that of corresponding concretes containing limestone aggregate, and the reduction in brittleness becomes more pronounced as compressive strength increases, a factor of great importance in the development of high-strength concretes. This phenomenon is reflected in the decrease in specific brittleness with increase in compressive strength for steel slag concretes, an effect that was not apparent for conventional concretes containing crushed limestone aggregate.

Fracture toughness, as determined by compact compression, was improved when steel slag aggregate was used, with K_{IC} values approximately 10% higher than those for concretes containing limestone aggregate.

11.2.3 Microlevel examination and the mechanism of modified properties

It is well known that in OPC concrete, the bond strength between aggregate and HCP (interface between HCP and inert natural mineral aggregate) is the weakest link in the composite (George & Sorrentino, 1982). The normal methods to improve bond include the use of aggregates with rough surfaces and porous structure, or the addition of superfine chemically active mineral additives, such as silica fume, superfine pumice, and zeolite power. These methods are intended to consolidate the interface bond physically or chemically. Steel slag inherently possesses both of these advantages in terms of physical and chemical strengthening. Additionally, compared with natural inert mineral aggregate, steel slag aggregate can react chemically with HCP mineral additive to some extent. It is envisaged that the development of steel slag as an aggregate for OPC concrete will be an inevitable trend in the years to come.

To investigate the mechanism of modified mechanical behavior, microlevel examination, including bond strength between steel slag aggregate and cement paste, microhardness in ITZs are examined.

As known, from the microscopic point of view, the interface between HCP and the aggregate is a weak link in normal cement concrete. This ITZ is a relatively porous zone extending generally to 30 μm or more away from contact with the aggregate surfaces, and less porous HCP beyond this zone (Rangaraju, Olek, & Diamond, 2010). The bond strength was studied by Zimbelmann (1985) and he showed that the bond strength between Portland cement paste and limestone is higher as compared to that between Portland cement and granite. Consequently he concluded that there was an added adhesion due to the chemical reaction between limestone and cement paste. Gao, Qian, Liu, Wang, and Li (2005) also reported that the weak ITZ between aggregate and cement paste was strengthened as a result of the pozzolanic reaction of ground granulated blast furnace slag (GBFS) and that the improvement was more significant with the decrease of particle size of the slag. This study explored bond strength and microhardness variation in the ITZ to determine the behavior of the aggregate–HCP interface, to investigate the hydraulicity of steel slag, and to compare the difference between the natural inert aggregate–HCP interface and steel slag aggregate–HCP interface.

11.2.3.1 Bond test

Test program

A series of tests were performed to determine the degree of the bond achieved between the aggregate and the matrix. Individual tests were carried out to determine the tensile splitting strength of the mortar (matrix), aggregate particle (ie, limestone or steel slag) (dispersed phase), aggregate/mortar (interface), and concrete. Tests were carried out for three different water/cement ratios (0.30, 0.35, and 0.40). The experimental program for the bond test is represented in Table 11.8. The size of specimens was 30×30×30 mm. Tensile splitting strength on the 30 mm cubes were taken as an indication of bond strength. The specimens for the tensile splitting strength tests are shown in Fig. 11.11A and B.

The load applied on the concrete specimen induces tensile and shear stresses on the aggregate particles inside the specimen, leading to the bond failure between the aggregate particles and the cement paste.

Results

Experimental results of the bond tests are shown in Table 11.9. Examination of the results shows that the tensile splitting strength of steel slag is approximately 17% higher than that of crushed limestone. This is partly due to the result of the higher specific gravity of the slag (3.61) compared with that of the crushed limestone (2.54). Also, the steel slag particles are more porous than limestone, resulting in higher water absorption (2.5% cf. 2.3%) and free water content (1.4% cf. 1.05%). Finally, the aggregate crushing value of steel slag is lower than that of limestone (4.8% cf. 8.7%).

The bond strengths between steel slag and mortar are higher than those between crushed limestone and mortar. The relative increase in bond strength is dependent on the water/cement ratio used for the mortar, with the greatest increase in strength for the three water/cement ratios being 13% (0.30), 27% (0.35), and 50% (0.40). Tensile splitting strengths of concrete containing steel slag as coarse aggregate are higher than those of concrete containing crushed limestone. The relative increases are similar to those for bond strength, being 15% (0.30), 30% (0.35), and 42% (0.40). The tensile ratios of σ_{Inter} to σ_{Matrix} and σ_{Inter} to $\sigma_{\text{Disp.}}$ are generally higher for steel slag aggregate than for limestone aggregate. The improvement in interface strength results in a stronger composite material (Table 11.10).

Tensile splitting strength of steel slag is greater than that of limestone aggregate. Bond strengths of the instant chilled slag–mortar interface are higher than those of the limestone aggregate–mortar interface.

The interfacial region between steel slag and mortar or HCP appears to be enhanced. It is considered that this is a result of chemical reaction and mechanical interlock due to the angular shape and texture of the steel slag.

11.2.3.2 Microhardness test

Microhardness testing is a technique by which the hardness of small individual features of metallic, mineral, or HCP specimens may be measured. It can also be used to determine the hardness of very thin sheets and wires. Microhardness is a comprehensive

Table 11.8 Bond test program: Matrix, aggregate, and matrix–aggregate interface

				Mix proportion type (water/cement ratio)		
				1	2	3
Mix no.	**Phase**	**Materials**	**Specimen size (mm)**	***W/C* = 0.30**	***W/C* = 0.35**	***W/C* = 0.40**
1	Matrix	Mortar (cement, sand)	30 × 30 × 30	Cement:sand = 1:2		
2	Dispersed phase	Limestone	30 × 30 × 30	Sawn, not polished		
		Steel slag	30 × 30 × 30			
3	Interface	Limestone + mortar	Two 30 × 30 × 15 combined	Cement:sand = 1:2		
		Steel slag + mortar	Two 30 × 30 × 15 combined			
4	Concrete	Limestone aggregate	30 × 30 × 30	Cement:sand:limestone = 1:2:3.5		
		Steel slag aggregate	30 × 30 × 30	Cement:sand:steel slag = 1:2:3.5		

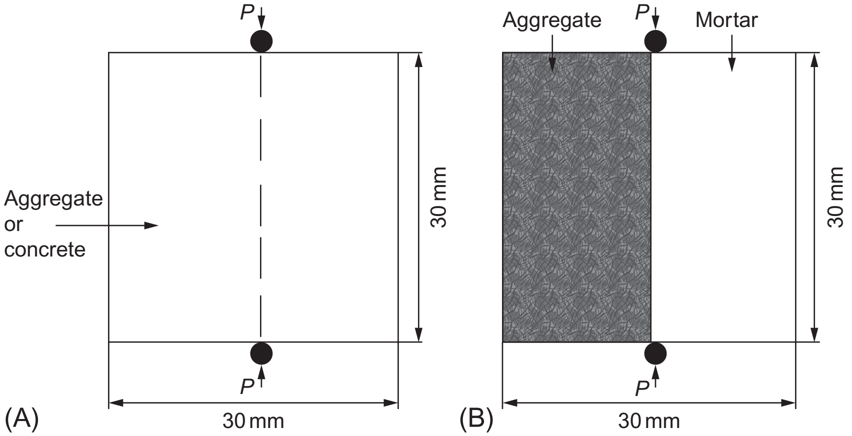

Fig. 11.11 Specimens for tensile splitting strength (A) and (B).

Table 11.9 **Experimental results of bond tests**

			Tensile splitting strength (MPa)		
			1	**2**	**3**
Mix no.	**Phase**	**Materials**	***W/C*=0.3**	***W/C*=0.35**	***W/C*=0.4**
1	Matrix	Mortar (cement–sand)	3.8	3.1	2.6
2	Dispersed phase	Limestone	4.6		
		Steel slag	5.4		
3	Interface	Limestone and mortar	1.5	1.1	0.8
		Steel slag and mortar	1.7	1.4	1.2
4	Concrete	Limestone aggregate	2.6	2.0	1.2
		Steel slag aggregate	3.0	2.6	1.7

Table 11.10 **Strength ratio of phases**

Ratio		**1**	**2**	**3**	**Mean**
$\sigma_{\text{Inter}}/\sigma_{\text{Matrix}}$	Crushed limestone	0.39	0.35	0.31	0.35
	Steel slag	0.45	0.45	0.46	0.45
$\sigma_{\text{Inter}}/\sigma_{\text{Disp.}}$	Crushed limestone	0.33	0.24	0.17	0.25
	Steel slag	0.31	0.26	0.22	0.26

parameter for various characteristics of ITZ. Tamimi (1994) used the Vickers microhardness test to measure the hardness in the cement paste of concrete and detected a drop in the hardness in the ITZ around aggregate. In this study, the test has been used to measure the hardness of the interfacial zone between steel slag aggregate and HCP. The indenter used is a standard Vickers diamond pyramid, having a square base and an apical angle of 136 degree.

The microhardness is expressed as the ratio between the load applied and the area of the resulting indentation, in GPa. For a given load, the diagonal length of the indentation is measured, and the hardness is determined from tables. Alternatively, the hardness may be calculated from Eq. (11.2).

$$\text{Micro hardness}, H_v = 1.185P/d^2 \tag{11.2}$$

where P is the applied load (N) and d is the mean diagonal length (mm).

A Leitz Watzlaz hardness tester was used in this investigation.

Experiment setup

Two groups of special concrete specimens were prepared for microhardness tests. For Group 1, special concrete specimens using normal Portland cement and air-cooled coarse steel slag aggregate, excluding fine aggregate, were prepared for the microhardness test. Control specimens for Group 1 were prepared using crushed limestone as the coarse aggregate and excluding fine aggregate. For Group 2, special concrete specimens using normal Portland cement and instant chilled coarse steel slag aggregate, excluding fine aggregate, were prepared. Control specimens for Group 2 were prepared using silica sand aggregate and excluding coarse aggregate. The mix ratio for normal Portland cement to aggregate was 1 + 1 and the water/cement ratio was 0.38. Before mixing, the coarse aggregate and silica sand were cleaned with water and brushed to ensure that the surface of the aggregate was clean. This process was carried out to avoid the mingling of very fine particles or dust, which could affect the test results. The experimental setup for the microhardness test is represented in Table 11.11.

Table 11.11 **Experimental setup of microhardness test**

Group	Specimen	Cement	Fine aggregate (FA)	Coarse aggregate (CA)
1	Control	1 Part OPC	None	1 Part crushed limestone
	Test	1 Part OPC	None	1 Part air-cooled slag coarse aggregate
2	Control	1 Part OPC	1 Part silica sand and aggregate	None
	Test	1 Part OPC	None	1 Part instant chilled slag coarse aggregate

Cylinders that were 100 mm in diameter, containing air-cooled slag, instant chilled slag, limestone, or silica sand, were made for each mix, and cured in water at 23°C (73°F) until the date of testing. The specimens in this study were tested at 28 days curing. The cylindrical specimens were cut, using a diamond impregnated saw, into slices ranging from 6–8 mm in thickness. The slices were trimmed to a cylindrical or cube-shaped cross section of about 20 cm^2 before hardness testing. The slices were subsequently coarse polished and fine polished using emery papers and then dried. The purpose of polishing was to enable the interface between the HCP and the aggregate in question to be distinguished under an optical microscope. The typical test positions and test points are illustrated in Fig. 11.12A and B.

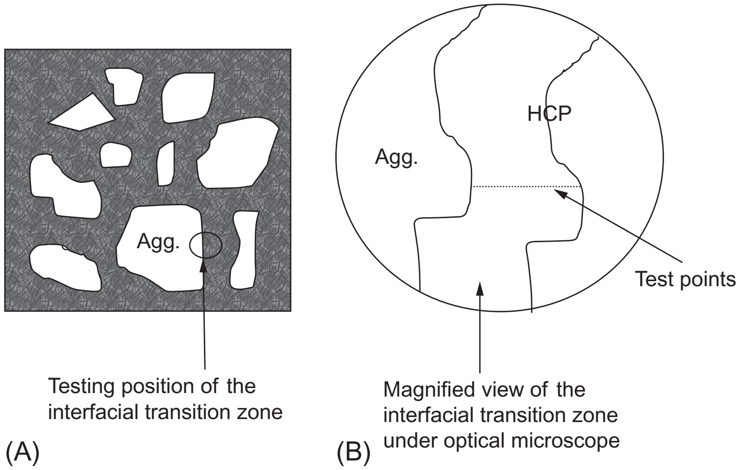

Fig. 11.12 Schematic drawing of tested position of ITZ. (A) Schematic drawing of test position in specimen slices and (B) the magnification of test position.

Measurement of the microhardness was carried out in the HCP adjacent to the aggregate particle. It is not necessary to keep the test points in the same line, as shown in Fig. 11.12B, however, accurate measurement of the distance from the aggregate particle is important. Also, careful selection of the test points within the HCP is important so that no fine particles or fragments of coarse aggregate are inadvertently tested. Before the test is carried out, an appropriate surcharge weight should be chosen for the materials to be tested. For the test described, a 200 g weight was employed for the coarse aggregate and a 50 g weight was used for the HCP.

Results

Microhardness measurements were made on the sawn surfaces of specimens to determine variation in hardness throughout the interfacial region between steel slag (fine particle size material = 3 mm diameter) and cement paste and sand grains and cement paste.

The microhardness results are shown in Tables 11.12, 11.13 and Fig. 11.13. Microhardness, and hence strength, varied with distance from the aggregate particle. Results indicate that within about 100 μm distance from aggregate surface ICSS aggregate performed better. Average hardness of instant chilled slag aggregate in the ITZ is 1.05 GPa compared with 0.95 GPa of air-cooled slag aggregate. Hardness in the ITZ of silica sand as aggregate in the concrete is 0.89 GPa and that of limestone as coarse aggregate in concrete is 0.52 GPa. The role of slag in consolidating HCP by better hydration within the ITZ is clearly seen from these experiments. In other words, the presence of the steel slag enhances the chemical reaction in the concrete. This chemical contribution from the slag is in addition to the likely increase in bond strength due to the rough surface texture of the steel slag.

Table 11.12 **Test results of microhardness of interface transition zone between aggregate (air-cooled steel slag and limestone) and HCP**

Interface between steel slag (air-cooled) and HCP		**Interface between limestone and HCP**	
Distance to aggregate, *d* (μm)	**Microhardness, H_{v50} (GPa)**	**Distance to aggregate, *d* (μm)**	**Microhardness, H_{v50} (GPa)**
10.1	2.06	8.2	0.57
25.0	1.06	38.2	0.55
43.2	0.70	43.6	0.57
59.8	0.61	67.0	0.43
77.0	0.25	100	0.50
123.0	1.01	–	–
Average hardness	0.95	Average hardness	0.52
Hardness of steel slag (air-cooled)	$H_{v200}=3.51$	Hardness of limestone	$H_{v200}=4.32$

Table 11.13 **Test results of microhardness of interface transition zone between aggregate (instant chilled steel slag and silica sand) and HCP**

Interface between steel slag (instant chilled) and HCP		**Interface between silica sand HCP**	
Distance to aggregate, *d* (μm)	**Microhardness, H_{v50} (GPa)**	**Distance to aggregate, *d* (μm)**	**Microhardness, H_{v50} (GPa)**
3.9	1.31	20.9	1.17
22.4	1.12	35.2	0.92
31.5	1.03	43.6	0.84
55.0	0.91	60.3	0.72
98.6	0.85	106.3	0.83
145.9	1.07	121.1	0.87
Average hardness	1.05	Average hardness	0.89
Hardness of steel slag (instant chilled)	$H_{v200}=5.51$	Hardness of silica sand	$H_{v200}=8.24$

Distributions of microhardness in the transition zone of interface between the aggregate particles and the HCP are shown in Fig. 11.13.

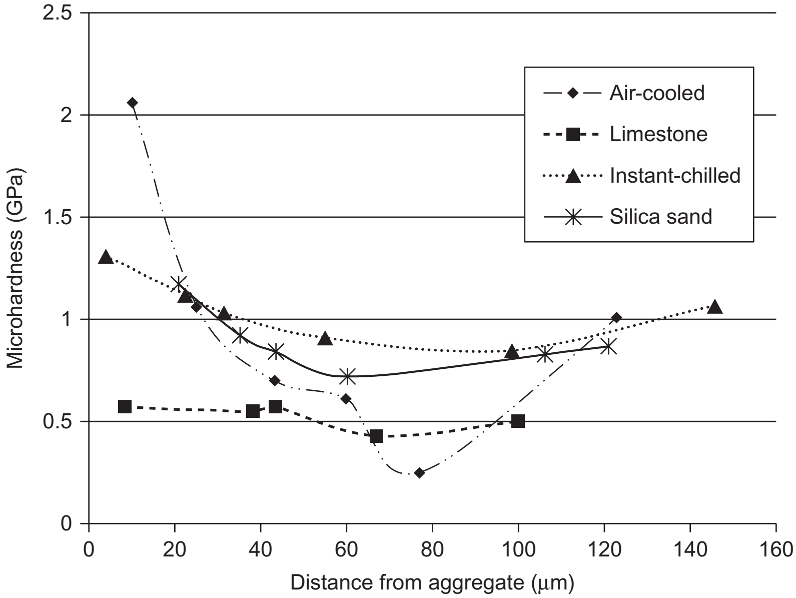

Fig. 11.13 Microhardness of ITZ between aggregate and HCP.

Maximum values of microhardness occur in the cement paste in close vicinity to the aggregate, at distances up to 25 μm from the interface, for both sand and slag particles. In the region 25–100 μm from the interface the microhardness values, at 28 days, for slag–paste composite are considerably higher than those for the sand–paste composite. At distances greater than 100 μm from the interface, hardness values are comparable for both composites.

For both composites, at both ages, hardness decreases with increasing distance from the interface in the region to 100 μm. At further distances from the interface the hardness gradually increases, thus exhibiting a pessimum value range for all composites. In general the pessimum values for slag–paste composites are slightly farther from the interface than those for the sand–paste composites.

The microhardness of air-cooled basic oxygen steel slag and ICSS is close to that of limestone and is lower than that of silica sand. The microhardness of the HCP side in the ITZ incorporating both air cooled steel slag and instant chilled steel slag is higher than that of the interface between limestone–silica sand and normal Portland cement. It is more obvious for instant chilled steel slag. Bond strength of instant chilled slag and HCP is greater than limestone aggregate. The enhancement of the interfacial region between steel slag and HCP is attributed to the chemical reactions and the mechanical interlock due to the angular shape and texture of steel slag.

The behavior strength of mixes incorporating steel slag can be explained by the steady and expansive compounds and chemical evolution over time in the ITZ. The calcium carbonate that is observed (Arribas, Santamaria, Ruiz, Ortega-Lopez, & Manso, 2015) enhances the cohesiveness, stiffness, and strength of this zone and, as a consequence, of the hydraulic concrete.

11.3 Development of slag aggregate use in rigid matrixes

Many researchers around the world, including Japan, Greece, Spain, Germany, Australia, Italy, Canada, India, and Saudi Arabia, have conducted research in laboratory and field trials on concrete containing slag aggregate, mainly steel slag. Due to the inherent expansion nature of steel slag, and cases of pavement failure, steel slag is currently not suitable and permitted for practical use in the concrete industry. For example, in the United States, steel slag aggregate is not permitted to be used as concrete aggregate, although some departments of transportation allow its use as an aggregate in HMA (Fronek, 2011). In Korea, the national standard specification for concrete states that steel slag aggregate must not be used in concrete (Moon, Yoo, & Kim, 2002). The research and development has not been balanced. Much of the research work conducted shows that properly aged steel slag can be nonexpansive when used in PCC (Fronek et al., 2012). Most researchers expressed optimistic views and envisioned the use steel slag in concrete in the near future to enter the construction market based on their thorough laboratory and field research studies (Anastasiou & Papayianni, 2006; Kawamura et al., 1983; Nadeem & Pofale, 2012).

Many cases have shown the success of using ACBFS in concrete applications (eg, concrete pavement). The experience indicated it is essential that engineers and contractors who use ACBFS aggregates in concrete understand the unique properties of the slag to make sure that proper quality control measures and the expected performance of the end product is achieved (Hiraskar & Patil, 2013; Jahangirnejad et al., 2013). This section focuses on steel slag and other nonferrous slag use in concrete and rigid matrices.

11.3.1 Steel slag use in concrete

11.3.1.1 Strength and mechanical properties

Much research has been done on strength and mechanical properties of steel slag aggregate concrete, and the chemical and mineral properties and their effect on concrete (Rojas & Rojas, 2004). The methods are generally to replace natural aggregate, coarse and/or fine, by steel slag aggregate, or blend use with other natural or by-products (eg, fly ash and steel slag) (Sinha, 2014; Sumi & Malathy, 2013; Yi et al., 2012).

Papayianni and Anastasiou (2010) used electric arc furnace (EAF) slag as a concrete aggregate, and ground ladle furnace (LF) slag as a supplementary cementing material to make concrete for use in heavy-traffic road pavements or in high-requirements industrial floors, with a 500 m long pilot road pavement mixed in a ready-mixed concrete plant. A survey conducted on the road after 10 years of continuous use showed that it performed in an excellent way with high strength up to 70 MPa. The concrete met the durability requirements for application in road pavements, airport or marine port fields, paving blocks, or industrial floors. The study also shows that mortar mixes with 20% cement was replaced by ground ladle slag and developed 90–95% of the reference mortar strength. A pilot production of shotcrete with LF slag proved very successful.

Pellegrino and Gaddo (2009) conducted research on concrete made with EAF slag as aggregate that showed good strength characteristics and total comparability (or even better) with those of traditional concrete. It is suggested the durability of the concrete can be strongly improved even in critical freezing–thawing environmental conditions by a small amount of air-entraining agent.

A study on the use of EAF slag in concrete showed that high substitution ratios of coarse natural aggregates by EAF slag are possible without decreasing mechanical properties of concrete; however, conversely, replacement of fine natural aggregates seems feasible at lower substitution ratios only (Pellegrino, Cavagnis, Faleschini, & Brunelli, 2013).

Qasrawi, Shalabi, and Asi (2009) used fine steel slag to replace sand in concrete. The tensile strength was increased by 1.4–2.4 times of normal concrete when the replacement is in the range of 30–50%. The compressive strength is increased for concrete by 1.1–1.3 times when the replacement is in the range of 15–30%. Therefore, the use of steel slag in concrete would enhance the strength of concrete, especially tensile strength, provided the correct ratio is used.

Qasrawi (2014) found that concrete with pure recycled concrete aggregate (RCA) causes strength decrease; however, if 67% of steel slag aggregate with 33% RCA blend is used it can increase the strength of the concrete.

Carbonated granulated steel slag aggregate was used to replace common natural aggregate in concrete. The results showed that carbonation treatments can significantly improve the strength and volume stability and reduce water absorption, porosity, and free calcium oxide of the slag and concrete. The workability of concrete with the slag was not significantly affected by the high water absorption. Besides, there was less bleeding and segregation and the porosity of the cement matrix was greatly reduced. After carbonation, harmful pores in aggregate were reduced by 24.4% while harmless pores increased by 67.9%. Strength of concrete exceeded the control concrete at 60 days (Pang, Zhou, & Xu, 2015).

11.3.1.2 Durability

The durability of the concrete containing EAF slag aggregate was analyzed in comparison with the fundamental requirements of the structural concrete. The steel slag aggregate concrete showed better behavior than the limestone concrete. The limestone concrete lost strength, but the strength of the concrete with EAF slag (CEAF) slightly increased from the outset. This improvement could be attributed to the fact that there was no loss of adhesion between the aggregate and the matrix, a loss that was observed in the reference concrete around its aggregates. Following exposure to high temperature and relative humidity, the CEAF has proven itself to be a more stable concrete than the ordinary concrete with regard to linear expansion and contraction, with no appreciable external signs of physical deterioration or loss of mechanical compressive strength (which even increased). There was less expansion in the slag mortars than in the reference mortar as a result of the sulfate attack, which after one year of exposure did not exceed the standard threshold (ASTM C452). Over time, these slag mortars showed a greater increase of strength than the reference concrete, thereby confirming the absence of internal damage and the null reactivity of the fine fraction of the slag aggregate. As regards the aggregate–alkali reaction, the expansion of the slag aggregate mortars did not exceed the limit and may, therefore, be considered nonreactive when used in cement mixes. With regard to the exposure of the concretes to sea tides, chloride penetration was greater (or similar) in the CEAF than in the reference concrete (CR). Finally, the corrosion of the steel rebars in the reinforced EAF slag concrete, after a year in the tidal seawater environment, showed greater susceptibility to corrosion than in the limestone reference concrete. The study confirms the viability of producing steel-reinforced concrete with slag aggregate (Arribas, Vegas, San-Jose, & Manso, 2014).

Other researchers (Brand & Roesler, 2015) also confirmed that steel slag aggregates in concrete can produce acceptable strength properties, suitable freeze–thaw durability, and exceptional fracture properties.

When using EAF slag concrete, high compressive strength and low water penetration should be the main characteristics to ensure the correct level of durability. Systematic testing to verify the efficiency of slag stabilization treatment is strongly suggested as such measures allow any possible expansivity to be carefully monitored. Research conducted by Manso, Polanco, Losañez, and González (2006) shows that the performance of EAF slag concrete is similar to that of a more traditional concrete in terms of its strength and slightly less so in terms of its durability. The high porosity of EAF slag is an obstacle to making a concrete resistant to freezing. Eventual improvements can be done by adding specific admixtures.

11.3.1.3 Workability

Study has shown that the workability of steel slag aggregate concrete can be maintained by adjusting the fine particle portion and W/C ratio. The more porous slag aggregates could perform quite well in slag concrete for structural purposes, as the three main properties (workability, and physical and mechanical aspects) are well balanced. Higher steel slag content may absorb much higher amounts of water than the natural aggregates, which is a very relevant question for concrete workability and effective W/C ratio. EAF concrete workability improves as the percentage of fine slag is replaced by fine natural aggregates or in the smaller-sized portion (sizes between 0 and 1 mm) of slag. An Abrams cone slump of 200 mm can be reached (San-Jose, Vegas, Arribas, & Marcos, 2014).

11.3.1.4 Practical use

A concrete structure that incorporated black steel slag was constructed as the foundation for the Kubik building laboratory. The results set out in this study cover the dosage phases of the steel slag aggregate concrete, with volumes of over 75% black slag. It is a pioneering structural application involving slightly over 140 m^3 (cu yd) of reinforced concrete (basement walls and foundation slab), which was manufactured in a concrete factory (Hormigones y Minas SA) and poured on-site without interruption by means of a concrete pump. This is principally due to it being a relatively low-cost, easily manufactured material, which has excellent qualities, both in terms of durability and mechanical strength (Arribas, San-Jose, Vegas, Hurtado, & Chica, 2010).

11.3.1.5 Blend use with other materials

Research and practice have proved that use slag aggregate with one or more natural materials or by-products can improve the properties of the end products that slag or one by-product may not be able to achieve, creating a win–win situation. Many slag aggregate concrete research programs have included other nonconventional material(s). This will be the trend in the use of industrial solid wastes in construction.

Liu, Zha, and Chen (2011) used fine steel slag aggregate with fine scrap tire particles in concrete and found that both the strength and the volume stability of scrap tire particle modified steel slag concrete are satisfactory, with similar strength properties to conventional concrete and obvious lower volume deformation change.

Brand and Roesler (2014) reported fractionated reclaimed asphalt pavement (FRAP) and steel slag reclaimed asphalt pavement were used in concrete. 50% dolomite FRAP and 20% steel slag FRAP can be used in concrete. Autoclave expansion tests of the steel furnace slag (SFS) FRAP with the asphalt binder resulted in contraction rather than expansion. Concrete tests revealed that the strength, modulus, shrinkage, and fracture properties were similar between concretes with SFS FRAP and with dolomite FRAP.

Manso, Gonzalez, and Polanco (2004) pointed out that it is very important not to mix the oxidizing EAF slag with other expansive slag (ie, reducing LF slag) in the factory, because this may have harmful effects on the material. Additionally, it is important to find the best proportioning mixtures that will produce concrete with the required properties in both fresh and hardened states.

Two types of steel slag aggregates were used in concrete. At the age of 56 days concrete specimens have been exposed to high temperatures up to 800°C (1472°F). Upon cooling of the specimens their residual properties (compressive strength, modulus of elasticity, weight loss, and ultrasonic pulse velocity) were tested and compared with the same properties of the reference concrete. The obtained results showed that slag could improve fire performance of concrete in a temperature range up to 400°C (752°F). This improvement is especially observable in the case of concrete made with thermally treated slag (Netingera, Rukavinab, & Mladenovič, 2013).

11.3.1.6 Alkali-aggregate reactivity check

In addition to volume stability testing of concrete containing slag aggregate, alkali-aggregate reactivity (AAR) tests, such as accelerated mortar bar for potential alkali-silicate reactivity (checking length change because of alkali-aggregate reaction in concrete prisms) and chemical method for potential alkali-silica reactivity of aggregate, should be conducted to assess the suitability of slag aggregate as a concrete aggregate. It should be noted that concrete containing slag aggregate that demonstrates volumetrically stable may show negatively in AAR testing. If a slag aggregate has potential for use as an aggregate in rigid matrices, parallel to the expansion and AAR tests, laboratory testing should demonstrate the effectiveness of supplementary cementing materials and chemical admixtures to prevent alkali-silica reaction. Testing also is recommended for the use of slag aggregate in rigid matrices such as PCC. Fig. 11.14 shows concrete containing air-cooled nickel slag after a mortar bar test.

Fig. 11.14 Concrete containing 12.7 mm (0.5 in.) air-cooled nickel slag after a 28-day mortar bar test.

Because of the exceeded expansion rate, this particular slag was not recommended for use as concrete aggregate, unless the additional content was adjusted, supplementary cementing materials, and/or chemical admixtures were used to lower the possibility of AAR.

11.3.2 Slag use in other rigid matrices

11.3.2.1 Slag use in brick making

Burnt clay brick has been one of the basic building materials used in construction activities since time immemorial. With the continuously rising demand for building bricks in the country (which is of the order of 70,000 million units per year at present), the reserves of alluvial soils suitable for making bricks are depleting day by day. Calcium silicate brick is considered to be one of the advanced building materials in India and is made from sand or siliceous' materials and lime. The production of such bricks requires high molding pressure and autoclaving for strength development. A considerable amount of energy is required in the production of clay bricks and calcium silicate bricks. In view of the huge demand for building bricks along with nonavailability of suitable soil, the need to explore alternative raw materials and energy-efficient technologies for making bricks has been realized. GBFS possesses inherent hydraulic properties. In preliminary studies carried out on small briquettes, it was observed that good quality bricks can be produced by pressing slag–lime mixture6 at sufficiently low pressure. The manufacturing process is quite simple as it does not require firing or autoclaving. Significant strength is obtained even by humid curing for the manufacture of slag–lime–sand bricks (Malhotra & Tehri, 1996). Investigations have been carried out into the development of bricks from GBFS. The study reveals that good quality bricks can be produced from a slag–lime mixture and sand by pressing the mix at a pressure of 50 kg/cm^2 (4.9 MPa). Bricks of wet compressive strength in the range of 80–150 kg/cm^2 (7.85–14.7 MPa) have been obtained after 28 days of humid curing at ambient temperature. Production of slag-based bricks consumes less energy compared to conventional burnt clay bricks or calcium silicate bricks.

Research focusing on the recycling feasibility of kaolin fine quarry residue (KFQR) combined with GBFS and granite–basalt fine quarry residue (GBFQR) to make a brick has been conducted. The brick was designed to be resistant to chemical actions, particularly sewage waters, and possesses better properties than the conventional one. The conventional brick is composed of clay, feldspar (precious material), and sand with different percentages. Solid briquettes were made from five suggested batches. These batches contained 50% of KFQR as a constant percentage, while the percentage of GBFS was increased from 10% to 40% at the expense of GBFQR percentage, which was decreased from 40% to 10% (by weight). Firing was performed from 1100°C to 1175°C (2147°F) at an interval of 25°C with 5°C/m (firing rate) and 4 h as the soaking time. To evaluate the possibility of making acid resisting brick (ARB), the fired specimens were characterized with respect to Egyptian Standard Specification (ESS) (ESS41-1986) as well as bulk density, volume changes, and firing weight loss. The study shows that the batch S2 containing 50% KFQR, 20% GBFQR, and 30% GBFS fired at 1125°C exhibits the most satisfying ceramic properties that meet the ESS requirements for making ARB (El-Mahllawy, 2008).

Korany and El-Haggar (2001) used BOF and EAF slags to replace coarse aggregates in producing cement masonry bricks and paving interlock units in Egypt. The slag replacement levels were 33%, 67%, and 100%. All masonry brick units made with slag showed higher bulk density values than the control. Water absorption values for all masonry brick groups were either comparable to or slightly higher than those of the control bricks but well below the ASTM limit of 13%. Substantially higher compressive strength results were reached for all masonry groups at 28-day age compared to the control ones and higher than the ASTM required 4.14 MPa (600 psi) for nonload-bearing masonry units at 3 days. At 100% replacement level, all groups resulted in compressive strength higher than the ASTM required 13.1 MPa (1900 psi) for load-bearing units at 7-day age.

11.3.2.2 Self-packing concrete

LF slag was used as filler in a laboratory study with steel fibers as reinforcement to make self-compacting concrete mixtures. Different contents of LF slag filler, ranging from 60 to 120 kg/m^3, and steel fibers, ranging from 0% to 0.7%, were used. The test results showed that LF slag can be used as filler for self-compacting concrete, as adequate consistency and workability was achieved, while compressive strength and durability were improved. LF slag can also be combined with steel fibers, which considerably increase fracture toughness, to produce a high-performance self-compacting concrete using a low-cost industrial by-product such as LF slag (Anastasiou, Papayianni, & Papachristoforou, 2014).

11.3.3 Nonferrous slag use in concrete

Nonferrous slag and nonmetallurgical slag use in concreting or brick making have been reported in recent years, including the use of copper slag (Gorai, Jana, & Premchand, 2003; Murari, Siddique, & Jain, 2015; Shi, Meyer, & Behnood, 2008a), the use of lead–zinc slag (Alwaeli, 2013), the use of ferrochromium slag (Zelić, 2005), and the use of incinerator slag (Lin, 2006).

11.3.3.1 Copper slag use as a fine aggregate

Many concrete engineers are eager to find fine aggregate sources other than the traditional river and sea sand. Fine copper slag aggregate is expected to be one of the alternatives near the copper slag available location. The carbonated thickness, resistance to freezing and thawing, thermal resistance shrinkage strain, creep, and setting time have been examined. The strength, slump, and durability of concrete with copper slag are not inferior to the same features of normal concrete. In general, the compressive and tensile strengths of concrete specimens containing fine or coarse copper slag aggregates are the same as that of normal concrete and significantly more than control mixes (Ayano & Sakata, 2000; Shi et al., 2008a). A report on the mechanical properties of high-strength concrete incorporating copper slag as a fine aggregate concluded that 40% copper slag as sand substitution can achieve a high-strength concrete that is comparable or better than the control mix (Hou, Chang, & Hwang, 2004). However, copper slag sometimes delays the setting time of concrete and low early strength gains were reported. The delay of setting time is more than 1 week in some cases although the durability in concrete is not affected by it. Research by Hwang and Laiw (1989) indicates similar trends of compressive strength development of concrete containing copper slag fine aggregate to those of mortars. The strengths of mixtures with 20–80% substitution of copper slag were higher than that of the control specimens. It was also noticed that the use of copper slag as fine aggregate could greatly increase the abrasion resistance of the cement mortar.

Hwang and Laiw (1989) and Ayano and Sakata (2000) reported that the shrinkage of specimens containing fine copper slag aggregate is similar or even less than that of specimens without copper slag. It was observed that the characteristic of the copper slag from Bahia, Brazil, was equivalent to the traditional aggregates or even better and it was used as an alternative to the admixtures used in concrete and mortars. In some regions, copper slag is permitted for use to replace natural sand in concrete. For example, in Singapore, the Building Construction Authority permits the replacement of sand by copper slag to a maximum of 10% by mass (Murari et al., 2015).

Investigation on the use of slag from copper smelting as fine aggregate in concrete was made with a cement/slag/water ratio of 1:2:0.55 and the ball milled slag gave higher strength. The effects of several kinds of slag in mortar and concrete on alkali aggregate reaction, reinforcing steel corrosion, abrasion, workability and slump, shrinkage and freezing–thawing characteristics were examined. Studies on the mechanical attributes of the epoxide and epoxide-asphalt concretes filled with used abrasive of the postcopper slag was carried out. It was found that the slag was a good filler for the concretes. Utilization of slag in cement raw material, Portland cement replacement in concrete, fill and ballast was investigated. The use of copper slag increased the compressive strength of concrete mixture. Copper slag was used as fine aggregate for concrete. They described the strength, setting time, and durability of concrete with copper slag (Gorai et al., 2003).

The copper slag obtained may exhibit pozzolanic activity and therefore may be used in the manufacture of addition-containing cements. Blends of copper slag with Portland cement generally possess properties equivalent to Portland cement containing fly ash, but very different to the silica fume incorporation. Copper slag and fly ash reduce the heat of hydration more effectively than silica fume in mortars. The replacement of 30% cement by copper slag reduces the flexural and compressive strength in a similar way to fly ash; however, after 28 days, the reduction is less than the percentage of substitution. The pozzolanic activity of copper slag is similar to that of fly ash and higher than silica fume. In the presence of low water/cement ratios, certain pozzolanic materials produce a very compact cement paste that limits the space available for hydration products, a determining factor in the formation of hydrated calcium aluminates. Scanning electron microscope (SEM) was found to be a useful analytical technique when aluminates are formed and can be clearly detected by X-ray diffractometry. Landfilling is not a desirable option for the disposal of solid hazardous and nonhazardous waste materials. It is not a viable method because of future environmental costs and problems associated with landfill regulations. This method increases load of toxic metals and other contaminants in the landfill, potentially increasing the threat to groundwater contamination. Increasing economic and financial factors also dictate that industry should look forward to recycling and reuse of waste material as a better option to landfills. Wastes and by-products can be used in addition to concrete without the need for large changes in its preparation. For all waste and by-product contents, the strengths increase as the curing time of the concrete increases. In general, it would be suitable for any application that does not require high strength, especially not in the short term. The porosity and the absorption coefficient increase with an increase in waste content and decrease as the curing time increased. The deformability of concrete also increases with the increase in waste contents. The density of the concrete decreases with an increase in waste content and increases as the curing time increases. Solidified materials are weak and contain significantly less cementitious materials and more water (eg, concrete). Due to waste addition, calcium-silicate-hydrate hydration is poisoned. In these situations, ettringite plays an important role; it increases strength and durability characteristics. Aggregate, which makes up 70% of the concrete volume, is one of the main constituent materials in concrete production. However, due to the high cost of natural sand used as a fine aggregate and the rising emphasis on sustainable construction, there is a need for the construction industry to search for alternative materials as fine aggregates in concrete production. Copper slag, which is the waste material produced in the extraction process of copper metal in refinery plants, has low cost, and its application as a fine aggregate in concrete production reaps many environmental benefits, such as waste recycling, and solves disposal problems. The fineness modulus of the combination of copper slag and fine aggregate was roughly 2.6, the optimum fineness modulus for concrete mix design. At this value, workability was found to be satisfactory with minimal bleeding. Addition of copper slag also improved the strength of the concrete. When the substitutional amounts exceeded 80%, lower strengths were obtained, possibly due to the formation of ettringite. It was also found that the effect of copper slag on long-term strength development was also dependent on the amount used and its fineness.

The effect of copper slag on the hydration of cement-based materials. Up to 15% by weight of copper slag was used as a Portland cement replacement. Activation of pozzolanic reactions was studied using up to 1.5% hydrated lime. Hydration reactions were monitored using quantitative X-ray diffraction, and the porosity was examined using mercury intrusion porosimetry (MIP). Results indicate a significant increase in the compressive strength for up to 90 days of hydration. A decrease in capillary porosity measured using MIP indicated densification of the microstructure (Murari et al., 2015).

11.3.3.2 The use of lead–zinc slag in concrete

Alwaeli (2013) reported that granulated lead–zinc slag (GLZS) was used to replace fine aggregate in concrete in the laboratory. The compressive strength and gamma radiation attenuation properties of the concrete were compared with those of ordinary concrete. The results indicate that the concrete mixed with GLZS as a sand replacement has higher strength. Concerning the absorption for gamma radiation, the results showed that the addition of GLZS resulted in an increase of the attenuation of gamma radiation. Consequently, these concretes could be used for construction of shields protecting personnel who work in laboratories where radiation is used.

11.3.3.3 Ferrochromium slag

It was reported that ferrochromium slag had been used as an aggregate in concrete pavement. With a proper selection of slag as an artificial aggregate, concrete pavements with higher compressive strengths, wear resistance, and specific weight than those of normal concrete were made. The 28-day compressive strength of the concretes made with ferrochromium slag and with limestone as aggregates (W/C = 0.64 and 350 kg/m^3) reached compressive strengths of 57.0 and 36.7 MPa (8265 and 5322 psi), respectively. Volume stability, high-volume mass, good abrasion resistance to wear, and crushability make this reinforced slag concrete suitable for wearing courses of concrete pavements for higher traffic load classes where carbonate stone material (limestone) mainly does not meet the requirements for cement concrete slab pavements (Zelić, 2005).

11.3.3.4 Municipal solid waste incinerator slag

Lin (2006) reported on a study dealing with the effect of municipal solid waste incinerator slag (MSWI) slag on fired clay bricks. Brick samples were heated to temperatures that varied from 800°C to 1000°C (1472–1832°F) for 6 h, with a heating rate of 10°C/min (50°F/min). The material properties of the resultant material were then determined, including speciation variation, loss on ignition, shrinkage, bulk density, 24-h absorption rate, and compressive strength. Toxicity Characteristic Leachate Procedure tests were also conducted. The results indicate that the heavy metal concentrations in the leachates met the current regulatory thresholds. Increasing the amount of MSWI slag resulted in a decrease in the water absorption rate and an increase in the compressive strength of the MSWI–slag bricks. The 24-h absorption rate and compressive strength of the MSWI–slag brick made from samples containing slag sintered at 1000°C all met the building requirements for second-class brick. The addition of MSWI slag to the mixture reduced the degree of firing shrinkage. This indicates that MSWI slag is indeed suitable for the partial replacement of clay in bricks.

11.3.3.5 Use of EAF slag in pervious concrete

To remedy the strength loss of pervious concrete, EAF slag produced at the Nucor Steel Hertford plant in North Carolina has been recently used to make pervious concrete that is proposed to be used for commercial parking lot paving in order to improve storm water drainage. The EAF slag is processed by MultiServ-Harsco (Fig. 11.15). The test is conducted in the Caterpillar & Gregory Poole construction lab at East Carolina University. The compressive strength of the concrete containing EAF slag is >28.3 MPA (>4100 psi), air void is >20%. Fig. 11.16 shows the pervious concrete containing coarse EAF slag aggregate before testing. Fig. 11.17 shows the permeability test of the pervious concrete containing coarse EAF slag aggregate.

Fig. 11.15 Air-cooled and water-quenched EAF slag from MultiServ-Harsco, Hertford, North Carolina has been used in pervious PCC. The results indicate the PCC possesses good physical and mechanical properties.

Fig. 11.16 Pervious concrete cylinders containing coarse EAF slag aggregate prior to compressive testing. It is competitive to normal aggregate concrete.

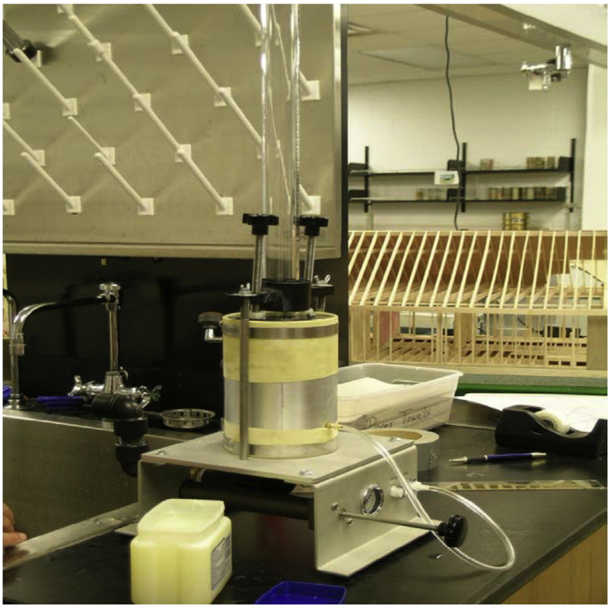

Fig. 11.17 Permeability test for the pervious concrete containing coarse EAF slag aggregate.

11.4 Summary

From the mechanical behavior investigated to concrete containing steel slag aggregate, it can be seen that the brittleness index of steel slag concrete is considerably less than that of limestone aggregate concrete with specific brittleness of the steel slag concretes decreasing as compressive strength is increased. Fracture toughness of the steel slag concretes is higher than that of corresponding control concretes containing limestone aggregate.

Bond tests have shown that the BOF slag exhibits higher interfacial bond splitting strength with cement mortar than that of limestone aggregate. The tensile splitting strength of the slag aggregate itself is higher than that of limestone. Compressive, indirect tensile and flexural strengths of steel slag concretes were greater than those of corresponding control concretes containing limestone aggregate. The interfacial zone between steel slag and HCP appears to be enhanced. Bond tests have shown that steel slag and cement paste exhibits higher interfacial bond splitting strength than natural aggregate and cement paste. Microhardness tests have shown that HCP is consolidated within about 60 μm from the aggregate particle. It is suggested that this is the result of a chemical reaction between the steel slag and cement paste coupled with mechanical interlock due to the texture of the steel slag.

Recent development and experience on the use of the slag aggregate, especially steel slag aggregate, in concrete have proved that quality steel slag aggregate can produce higher strength and durable concrete in laboratories. More field trials are necessary and the establishment of usability criteria is imperative.

Questions

11.1 What three phases are PCC systems comprised of?
11.2 What is the weakest link in the concrete structure?
11.3 Explain why concrete is a structural sensitive material.
11.4 Why can expansion force, not volumetric expansion, better assess the usability of steel slag used in a rigid matrix?
11.5 Explain what quality control procedures are critical in the use of slag aggregate in concrete.

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Usability criteria for slag use in rigid matrices

12

12.1 Introduction

The intention to use slag aggregate to replace natural aggregate in concrete is initially based on its availability and good characteristics. In addition, sustainable development of the construction industry and conservation of natural resources require using recycled and industrial coproducts of all kinds in construction (Brito & Saikia, 2013; USGS, 2010).

In the last approximately 30 years, research has been conducted on steel slag use as aggregates in concrete and its advantageous properties have been reported (Arribas, Santamaria, Ruiz, Ortega-Lopez, & Manso, 2015; Montgomery & Wang, 1992; Papayianni & Anastasiou, 2010; Sinha, 2014; Sumi & Malathy, 2013). The improvement and modification of concrete mainly come from the unique characteristics of steel slag. It is known that the properties of aggregate, including geometric shape, surface texture, chemical activity, and hydrophilicity have significant influence on bonding strength. Fig. 11.1 illustrates the effects from 10 different scenarios including aggregate shape, surface texture, and disrupt position. Fig. 12.1 compares the surface textures of different aggregates. Air-cooled and crushed steel slag, for example, possesses all the good physical and mechanical properties that are required for making concrete, even high-performance concrete.

Laboratory research and experimentations conducted on concretes containing steel slag have shown promising results. However, these results unsupported by thorough characterization and performance testing are not sufficient to encourage the use of a steel slag in concrete or other rigid matrices without misgivings or concerns. New test methods, usability criteria based on laboratory testing, theoretical deduction, and field verification are important to form the foundation for the use of slag aggregate in concrete.

The ASTM D4792-00 Standard Test Method for Potential Expansion of Steel Slag Aggregate from Hydration provides the method to determine the volumetric expansion as an indicator to evaluate the use of steel slag as an unbound granular material. However the volume expansion data are not directly related to the expansion behavior of steel slag under confined conditions such as in Portland cement concrete (PCC). New methods are needed to evaluate the steel slag aggregate in a rigid condition. This chapter introduces the criteria establishment based on new laboratory testing methods, mathematical and mechanical modeling for slag aggregate use as an aggregate in concrete. Steel slag is used as an example in the criteria deduction. The principles can be extended to other nonferrous slag aggregates.

The Utilization of Slag in Civil Infrastructure Construction. http://dx.doi.org/10.1016/B978-0-08-100381-7.00012-4

Fig. 12.1 Comparison of the texture and particle shape of different aggregates for concrete. (A) Electric arc furnace slag; (B) crushed stone; and (C) gravel.

12.2 Quantification for use in restrained conditions or rigid matrices

In this section, the concept of expansion force of steel slag in introduced. The test methods to determine the expansion force of both bulk volume of slag and single slag particle are developed. The expansion force of single slag particle, with other parameters, is used to deduce actual stress of a single unstable slag particle generated from the expansion force that is used in the development of usability criteria.

As known, in contrast to blast furnace slag, which is volumetrically stable and straightforward in its construction uses, steel slag contains hydratable oxides (CaO and/or MgO) that can result in volumetric instability (expansion) that must be dealt with through appropriate steel slag aging and quality control, especially suitable testing to ensure its appropriate use in construction. Particular care must be taken to prevent potential steel slag expansive behavior in confined applications; PCC, for instance. In the last approximately 30 years, research has been conducted on steel slag use as aggregates in concrete and its advantageous properties have been reported. The reason for steel slag not currently being fully utilized is often due to a general lack of quantification work on the properties of steel slag (expansion potential, for instance) and the performance required for end products. Appropriate test methods to quantify the expansive properties of steel slag is the first and most important step to develop technical guidance, criteria, and specifications for practical utilization of steel slag in concrete construction. The current ASTM standard test method for potential expansion of steel slag aggregate from hydration (ASTM, 2006) gives the method to determine the volume expansion of aggregate that can be used to evaluate the use of steel slag as an unbound granular material. However, the volume expansion data are not directly related to the expansion behavior of steel slag under confined conditions such as in PCC, building blocks, cement-treated base, or hot-mix asphalt (HMA) under lower temperatures. To use steel slag as an aggregate in rigid matrices, the expansion force of steel slag during its hydration reaction should be considered and measured.

12.2.1 The concept of expansion force

Although there are some noticeable benefits in mechanical properties of slag aggregate concretes compared with normal concrete, hinderances and restrictions exist currently on the use of steel slag as an aggregate in PCC and other restrained conditions or rigid matrices.

Different from use under nonrestrained conditions, such as granular material, when slag is used as an aggregate in a rigid matrix (as an aggregate in concrete, for instance), the rigid end product behaves differently from granular base material. It is important to have a thorough experimental investigation and theoretical analysis on mass of slag samples, a single slag aggregate particle, and the disruption mechanism of the end product.

It is well known that in PCC, the bond strength between aggregate and hardened cement paste (HCP) (interface between HCP and inert natural mineral aggregate) is the weakest link in the composite. The normal methods to improve bond include the use of aggregates with rough texture, or the addition of super-fine chemically active mineral additives, such as silica fume, pumice, and zeolite. These methods are intended to consolidate the interface bond physically and chemically. Steel slag inherently possesses both of these advantages in terms of physical and chemical strengthening. Additionally, compared with natural inert mineral aggregate, steel slag aggregate can react chemically with HCP and mineral additive to a certain extent.

As demonstrated in Chapter 6, the use of slag can be generally classified into four categories (Fig. 6.4). In keeping with the increase in the use of the potential chemical energy of slag from nil to full, the requirement relating to the stability of the slag is from lenient to rigorous, for example, due to the expansion property of the steel slag. This suggests that in applications where more potential chemical energy is utilized, higher degrees of stability in the slag are required and more quantitative work is needed.

The reasons for the limitation of steel slag as an aggregate in concrete arise mainly from two issues: (i) the variation of volume stability of steel slag per se (some concretes containing steel slag aggregate might disrupt due to volume expansion of steel slag particles) and (ii) the lack of experimental and theoretical work and the fact that there are no criteria developed to prove the relationship between the expansion property of steel slag and the stability of concrete containing steel slag. Note that, however, some steel slags do exist that are sufficiently stable to be used in cement concrete that have demonstrated sustainably and stable performance under rigorous treating conditions. There are also examples of disrupted concrete containing other steel slags that could be useful in ascertaining the uses of steel slag in concrete and for predicting the likelihood of, and extent of, disruption of the concrete with steel slag aggregate prior to use of the steel slag. Research work related to the latter has been neglected so far, perhaps due to the occurrence of isolated failures in practice.

In view of the benefits of steel slag aggregate concrete and based on the facts that some concrete, tested in the laboratory, performed well with similar or exceeding results to ordinary aggregate concrete, even under the autoclave condition or long-term water curing, questions that naturally arise include the following:

- **(i)** Under what degree of stability can a particular steel slag be practically and successfully used as an aggregate in a rigid matrix; for example, in cementing mortar matrix or HMA concrete under frigid temperature conditions? (Note that steel slag has been successfully used in HMA production, but some distresses have been reported, and criteria to predict and prevent the distresses need to be developed.)
- **(ii)** How to determine, measure, and assess the stability and expansion of steel slag for its use in rigid matrix (confined); concrete, as a typical example?

(iii) What is the basic disrupture mechanism of steel slag in concrete and to what extent does the steel slag aggregate particle expand, crack, and result in the disrupting of concrete?

(iv) How can the relationship between steel slag expansion characteristics and the constraining ability of the matrix in which steel slag acts as an aggregate (the matrix can be mortar) be established? This relationship needs to be proven theoretically and experimentally for concretes containing steel slag aggregate that are volume stable or unstable, and explanations need to be given as to why or why not they are stable or unstable. If successful, this should remove the doubts that exist about the use of steel slag as an aggregate in concrete. It will also suggest that the potential utilization of the chemical energy in steel slag, with rigorous quality control process, is possible.

These questions will be addressed, discussed, and solutions need to be sought.

12.2.1.1 Bulk expansion force P_e and three-dimensional expansion force per unit volume, σ_e

Considering a steel slag as an aggregate in concrete, the concepts of expansion force (Newton), rather than volume expansion (volume changes, %), which is discussed previously, should be considered.

The ultimate goal is to determine the plane stress that resulted from slag expansion; in other words, the maximum tensile stress in a slag particle, σ_t (MPa), to establish the relationship between this stress and the allowable tensile stress, F, of rigid composite materials, concrete for example. In this chapter, the expansion force generated by a single *unstable* slag particle is deduced. Actual maximum tensile stress from expansion force will be discussed in Section 12.3 based on a mechanical model. It is obvious that expansion force can be produced by either a single unstable slag particle or mass of slag particles, and the expansion force is directly related to the total volume of the particles. Therefore, four critical areas are

(i) How can the expansion force of bulk slag sample be measured and determined?
(ii) How can the expansion force of a single particle be determined?
(iii) How can the expansion force of a single particle be converted into plane tensile stress?
(iv) How can the usability criterion be established?

To answer these questions, it is needed to know the expansion force produced due to one particle of steel slag. The two test methods developed are presented in Section 12.2.2, which answers the first question above and forms the foundation of the establishment of slag usability criteria. Section 12.2.3 answers the second question. Experiments conducted in the laboratory prove the answers that are provided in Section 12.2.4. Questions 3 and 4 will be sought, discussed, and answered in Section 12.3.

From the volume expansion test shown in Section 12.2.2, if the slag sample is constrained in a rigid mold, but with freedom to expand in one direction, a volume expansion will occur. If the volume expansion is completely constrained, an internal expansion force will be produced. The total expansion force is related to, in an unquantified relationship, the volume of steel slag for a slag with a given f-CaO and periclase contents. That means that the larger the steel slag volume, the larger the expansion force that is generated. The expansion force is expressed as P_e and is defined as the resultant expansion force produced by a given volume of steel slag. It is found to be directly proportional to the volume of the steel slag.

The volumetric expansion force per unit volume, σ_e, is defined as P_e/V. It is proportional to the volume expansion (%). Therefore, the following corresponding relationships exist (proportionality constant):

Resultant expansion force (P_e) $\propto$ Volume of steel slag (V)
Expansion force per unit volume (σ_e) $\propto$ Volume expansion of steel slag (%)

It is possible to calculate the force P_e through experimental determination as discussed below. The expansion force is equal at all points throughout the bulk of steel slag. The greater the volume of steel slag, the larger the expansion force; however, σ_e is constant. Note that this applies only to the mass of steel slag particles in a compacted condition, it does not apply for the case of a single steel slag particle. It will be seen later that the effect on a single steel slag particle differs from that on a mass of steel slag particles. The three-dimensional definition of expansion force is monopolized by expansion of steel slag. It is necessary to avoid associating expansion force with compression or compressive stress or tension or tensile stress.

Fig. 12.2 presents an illustrated explanation of how the resultant expansion force depends on the volume of steel slag; that is, depends on the size of the three-dimensional unit.

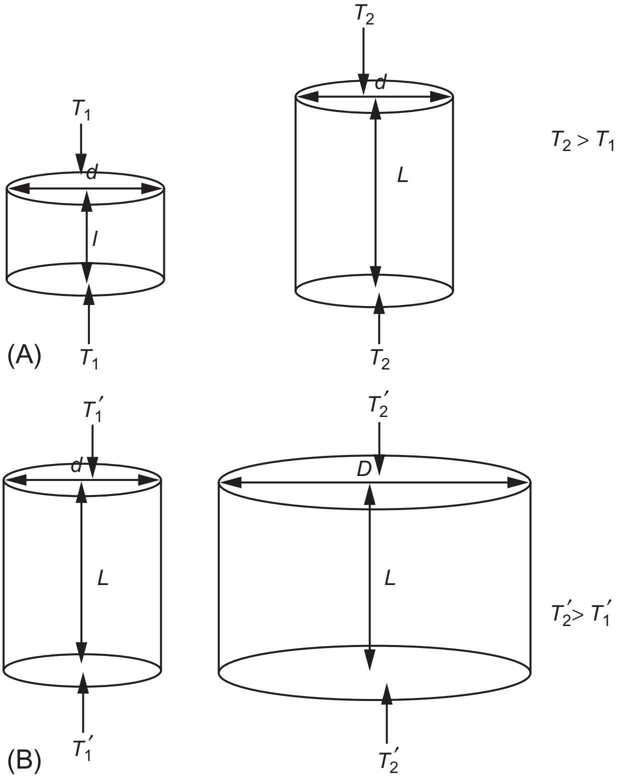

Fig. 12.2 Effect of size of the mold on expansion force.

In Fig. 12.2A, steel slag is contained in two molds with the same diameter and different heights, $T_2 > T_1$. In Fig. 12.2B, two molds have the same height and different diameters, $T_2' > T_1'$. In Fig. 12.2, T is the resultant expansion force experimentally measured on the cross-sectional area.

It must be noted that compressive stress from an external force or load is totally different from the expansion force resulting from internal expansion expansive slag material. Compressive stress in engineering-related situations is due to external force; while expansion force is generated by the material itself. It is necessary to distinguish between the two different forces when conducting the analysis of expansion force.

12.2.1.2 Difference A

As shown in Fig. 12.3A, for a solid specimen of given volume and constant thickness, undergoing expansion, the maximum load T_2 is larger in magnitude than load T_1 when the surface is restrained and exerts compression. The maximum load is independent of the volume of the specimen and is only related to the loading area. For a mass of steel slag compacted in a stiff mold, however, the expansion force produced by the mass of steel slag is variable dependent on the volume as shown in Fig. 12.2. However, the expansion force measured from any cross-sectional area of the steel slag sample is a constant value as shown in Figs. 12.3B and 12.4. Here, expansion force can be measured by means of load cell and rigid mold by multiplying by 6, as illustrated in Section 12.2.1.3. Detailed test procedures and apparatus are provided in Section 12.2.2.

To explain the latter (ie, the expansion force of steel slag), a model of steel slag particles in the mold is set up as shown in Fig. 12.4. It is assumed that the steel slag particles are saw-cut to cubes contained within a rigid mold.

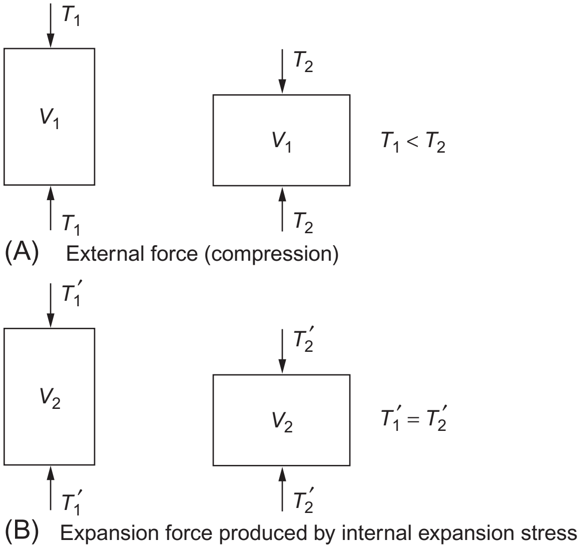

Fig. 12.3 The concept of expansion force and difference from external compression.

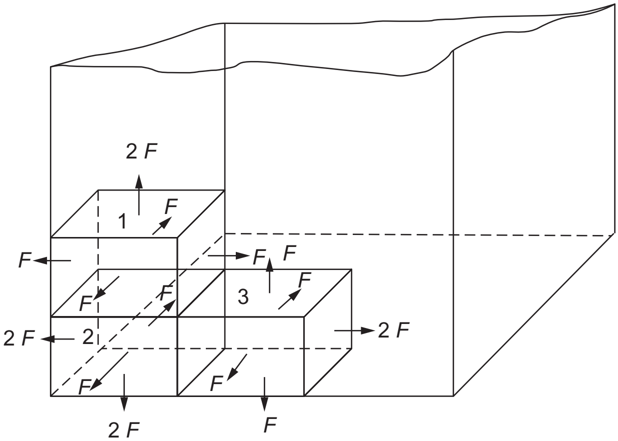

Fig. 12.4 Model of repeated addition of expansion force of steel slag in constrained mold.

In Fig. 12.4, three steel slag particles are taken and are analyzed. The resultant expansion force from particle 1 and particle 2 in the vertical direction is *2F* and, if the surface area is *S*, the "stress" will be *2F*/*S*. The resultant expansion force from particle 2 and particle 3 is the same in the horizontal direction. On the other hand, the expansion force from particle 1 in the horizontal direction is *F*, and the corresponding "stress" is *F*/*S*. This indicates that, although the resultant side surface expansion force *T* is constant, the force per unit area is variable dependent on position within the mold and is proportional to the number of steel slag particles within that area; that is, to the resultant apparent length of the mass of steel slag particles.

12.2.1.3 Difference B

For a uniaxial compressive specimen, such as a unit element, the stresses in the three directions, generally speaking, are not equal, as shown in Fig. 12.5.

$$(\varepsilon)=k\begin{bmatrix}1 & -\mu & -\mu\\ -\mu & 1 & -\mu\\ -\mu & -\mu & 1\end{bmatrix}(\sigma) \tag{12.1}$$

$$\varepsilon_x=k\left[\sigma_x-\mu\sigma_y-\mu\sigma_\theta\right]=0 \tag{12.2}$$

$$\varepsilon_y=k\left[-\mu\sigma_x+\sigma_y-\mu\sigma_\theta\right]=0 \tag{12.3}$$

$$\varepsilon_\theta=k\left[-\mu\sigma_x-\mu\sigma_y+\sigma_\theta\right]=0 \tag{12.4}$$

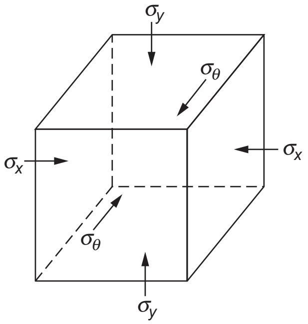

Fig. 12.5 Stresses on a unit element.

$$\sigma_y\left(1-\mu^2\right)=\mu\left(1+\mu\right)\sigma_x \tag{12.5}$$

$$\sigma_y=\frac{\mu\left(1+\mu\right)}{1-\mu^2}\sigma_x \tag{12.6}$$

$$\because \quad \mu\left(1+\mu\right)\neq 1-\mu^2 \tag{12.7}$$

$$\therefore \sigma_x\neq\sigma_y \tag{12.8}$$

Similarly, it can be shown that

$$\sigma_y\neq\sigma_\theta \tag{12.9}$$

However, the three-dimensional expansion force at any point in the steel slag has the same value.

The calculation includes two aspects: one is the calculation of the resultant expansion force, P_e, produced by a given volume of steel slag and the other is the volume expansion stress σ_e.

The calculation is carried out based on the expansion force experiment described in Section 12.3.2.2. Here, it is assumed that the partial surface expansion force *T* can be determined from the dial gauge reading obtained during the experiment.

The mold containing the steel slag is 12.8 cm high × 15.0 cm diameter with a volume of $V_c=2260\,\text{cm}^3$. *T* is determined from the load cell connected to the movable plate at the top of the mold. Is it possible to determine σ_e from *T*/*V*? The answer is no. From Fig. 12.2, *T* is the force acting on the top surface area, it is not the resultant expansion force of the whole volume of the steel slag, due to the fact that the steel slag expands in all directions.

Is it possible to use *T*/*A* to express the two-dimensional tension stress σ_t? The answer is also no, because

(i) The volume of slag sample contains both solid slag and voids. The area A does not express the real area occupied by the slag.

(ii) For slag samples in two cylinders with the same diameter, but with different heights, the expansion force $T_1 \neq T_2$ (Fig. 12.2). If two-dimensions are taken (ie, tensile stress due to expansion force $\sigma_t = T/A$), the stress σ_t would be different for the same steel slag as a result of changing the size of the mold.

(iii) T/A has nothing to do with the tension force on steel slag particles, which results in the cracking and it only represents the expansion force from one dimension.

It is assumed that the calculated resultant expansion force P_e is produced over the total surface area; that is, P_e is the summation of all the individual particle surface area expansion forces (T). From Fig. 12.2 this assumption is rational because the expansion force from every steel slag particle (if the steel slag particle is volumetrically unstable) will be transmitted to the outermost surface. The surface expansion force on the top and base is $2T$. The expansion force per unit area is called the virtual expansion stress σ_v and is denoted by T/A (Pa). From the analysis, the virtual expansion stress σ_v is related to the length of the sample and is not the same from one surface to another. The virtual expansion stress on the top and base area is the same; however, the virtual expansion stress on the side areas, σ_{vs}, is different from that on the top area. The side virtual expansion stress, σ_{vs}, is proportional to that on the top or base area, A, in terms of dimensional length; that is,

$$\frac{\sigma_v}{L} = \frac{\sigma_{vs}}{D} \tag{12.10}$$

$$\sigma_v = \frac{T}{A} \tag{12.11}$$

$$\sigma_{vs} = \sigma_v \times \frac{D}{L} \tag{12.12}$$

$$T_s = \sigma_{vs} \times A_s \tag{12.13}$$

$$P_e = 2T + T_s \tag{12.14}$$

where T_s is the side expansion force and A_s is the side area. That is,

$$P_e = 2T + \frac{T}{A} \times \frac{D}{L} \times \pi DL = 2T + \frac{4TD}{\pi D^2 L} \times \pi DL = 6T \tag{12.15}$$

This indicates that the resultant expansion stress, P_e, can be determined from the expansion force test in Section 12.2.2 with P_e being equal to six times the force (measured expansion force from testing) on the top area of the cylindrical mold. This is independent of the measured surface area. This suggests that if there are two molds, mold one with a 15 cm diameter and mold two with a 20 cm diameter, which have same volume, the force T measured for mold 1 and mold 2 will be the same and the resultant expansion forces of $6T$ for the two molds are the same.

12.2.2 Test methods development

Two test methods, the expansion force test and the autoclave disruption test, are introduced here to determine the expansion force generated by mass steel slag samples and a single steel slag aggregate particle.

12.2.2.1 Expansion force test

The expansion force test method has been developed to determine the expansion force generated by a given volume of coarse steel slag aggregate under the condition that the volume change is limited to zero. The expansion force is then converted into the expansion force of a single steel slag particle in a rigid matrix such as concrete. In this test, coarse steel slag samples were sieved into uniform particle size 16–20 mm for testing. Samples were washed before being placed in the testing mold. Due to the relatively low hydration process of steel slag, a 74 ± 3°C water bath was adopted to accelerate the hydration reaction (ASTM, 2006). This temperature range provides the environment to accelerate the hydration reaction of steel slag and also avoid fast water losing due to evaporation. The testing mold has perforated base plates to allow for moisture movement during the immersion of the test. The inner diameter of the mold is 150 mm, the area is 17,660 mm^2, and the height of the section containing samples is 128 mm. The volume is 2.26×10^6 mm^3. Fig. 12.6 gives the dimensions of the mold.

The mold was then immersed in a container filled with water maintained at 74 ± 3°C (Figs. 12.7 and 12.8). The slag sample was compacted in three layers with 56 blows per layer. A spacer disc was used. The container and the mold with samples were placed on the base platen of a stiff testing machine. A sensitive load cell was installed between the mold and the top platen of the testing machine. At the commencement of the test, an initial preload of approximately 10 N was applied. This is to ensure that there is sufficient support force between the top platen and the mold. Water was added daily to compensate for the water evaporated.

Load cell readings were taken on a daily basis, every 24 h. The readings from the load cell in Newton reflect the expansion force generated by the bulk steel slag sample in the testing mold. The readings are independent of the measured surface area if the volumes of testing molds are the same.

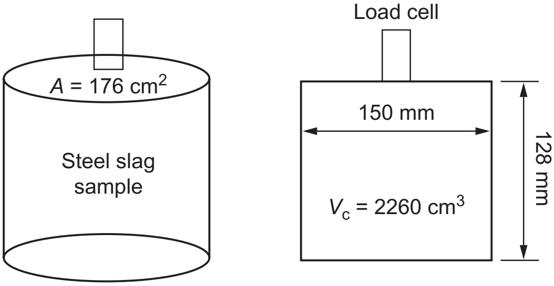

Fig. 12.6 Geometrical size of the mold.

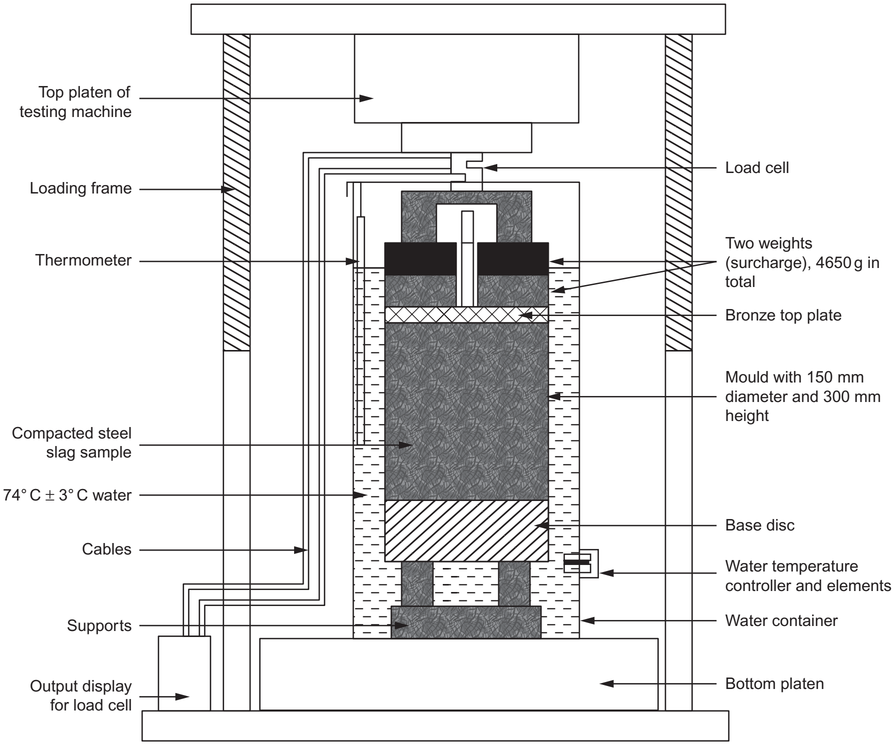

Fig. 12.7 Illustration of the apparatus for expansion force test.

Fig. 12.8 Apparatus for expansion force test.

12.2.2.2 Disruption ratio test

A laboratory autoclave disruption test has been developed parallel to the expansion force test to evaluate the volumetric stability of individual coarse steel slag aggregate particles. This is important. Because that volume expansion of steel slag really refers to the expansion of unstable slag participles; stable and unstable particles must be separated quantitatively and experimentally. Only the unstable particles are the object of the study. In this test, a steel slag sample is separated into different size fractions and examined petrographically. Specific amounts, normally 100 or 50, of slag particles are chosen to test each size fraction of the slag. The slag sample is then placed in an autoclave for testing. The autoclave for the disruption test was set at 357 kPa (51.8 psi), 137°C (279°F), for 1 h testing. The pressure is approximately 3.5 atm and was selected at the mid-range of the autoclave used in the testing. The temperature is the actual temperature measured. The disruption ratio is given by Eq. (12.16). The disruption ratio (R) is then used in evaluation of the expansion potential. It is also used in the calculation of expansion force of a single steel slag particle with the results of expansion force test

$$R = \frac{N_c}{N_t} \times 100\% \tag{12.16}$$

where N_c is the amount of particle cracked or powdered after test and N_t is the amount of particles selected for the test (see Figs. 12.9 and 12.10).

Fig. 12.9 Autoclave disruption test apparatus.

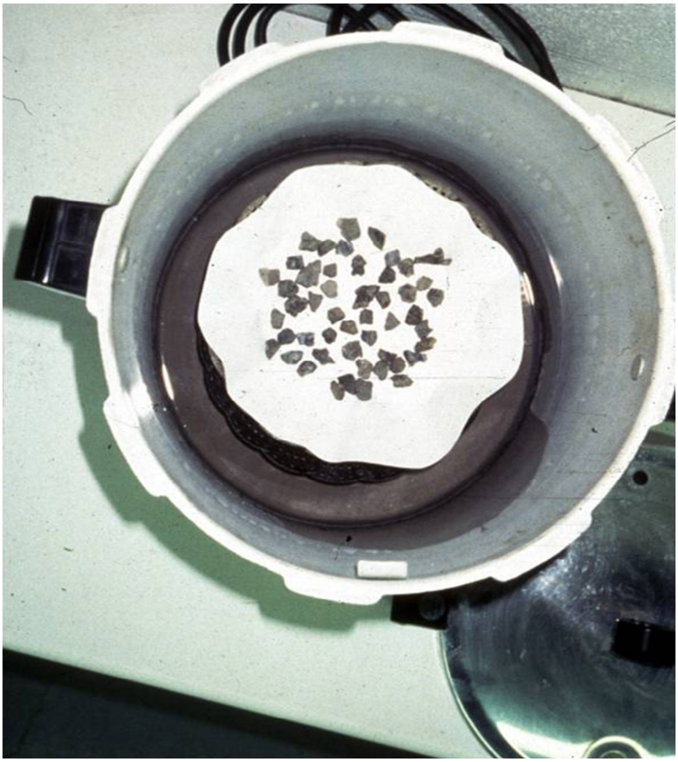

Fig. 12.10 View of slag particles following the autoclave disruption test.

12.2.3 Quantification of expansion forces

12.2.3.1 Quantification of expansion force of a single steel slag particle

For steel slag used as a coarse aggregate in a bound condition, or in a rigid matrix, such as PCC, the resulting integrity and volume stability are basically controlled by the minimum allowable stress of the matrix materials, cement mortar for instance, and the maximum expansion stress, which can be deduced from the expansion force based on appropriate modeling of steel slag particles in the matrix. A usability criterion for steel slag use in confined conditions can be developed by relating the allowable stress of a known matrix material and the maximum expansion force (stress) of a steel slag particle. Because concrete is a structurally sensitive material, one localized failure (one particle failure) will be regarded as failure of the concrete. Therefore the basic disruption model for steel slag concrete should be based on a single steel slag particle. The imperative task is to determine the expansion force of bulk steel slag and an individual steel slag particle.

From the expansion force test, if the bulk steel slag sample is placed in a rigid mold and the volume expansion is completely constrained, an internal expansion force will result. The expansion force is expressed as F_{ex} and is defined as the resultant expansion force produced by a given volume of steel slag. The expansion force is to be proportional to the volume of slag sample; that is, the greater the volume of the steel slag, the larger the expansion force will be.

The measured expansion force F_{ex} is produced by a given volume (V_{sl}) of steel slag. The expansion force of unit volume of steel slag, f_{ex}, is given by

$$f_{ex} = \frac{F_{ex}}{V_{sl}} \tag{12.17}$$

where f_{ex} is the expansion force generated by a dense compacted steel slag in a unit volume, (N/m^3); F_{ex} is the measured expansion force produced by a given volume of dense compacted steel slag, (N); and V_{sl} is the volume of compacted steel slag, (m^3). The expansion force of a unit volume of slag given by Eq. (12.17) is equal everywhere in a given volume of steel slag; that is, f_{ex} is a constant for a given slag sample. Note that this applies only to the large amount of steel slag particles in a compacted condition; it does not apply to a single steel slag particle. The three-dimensional expansion force is monopolized by expansion of steel slag in a confined condition. Both the disruption ratio, R, and expansion force, F_{ex}, will be used in quantifying the expansion force of steel slag.

The total expansion force produced from the steel slag per cubic meter of concrete, F_{ex}, can be expressed as

$$F_{ec} = f_{ex} V_{sc} \tag{12.18}$$

where F_{ec} is the expansion force produced by the coarse steel slag aggregate in one cubic meter of concrete, (N); V_{sc} is the volume of steel slag aggregate in one cubic meter of concrete, including air voids, based on the mix proportion, (m^3). From a given concrete mix proportion, with the weight of the steel slag coarse aggregate and the density of a given steel slag, F_{ec} can be calculated.

It is reasonable to assume that only the cracked or powdered steel slag particles that have undergone the autoclave disruption test contribute to the expansion force, and the disruption ratio is equivalent to the volumetric ratio. Therefore, the actual volume of expanded steel slag, (V_{se}), excluding air voids, is

$$V_{se} = V_{sc} R \Phi \tag{12.19}$$

where V_{se} is the actual volume of expanded steel slag particle in concrete, (m^3); Φ is the solid volume of spheres under tightly compacted condition, which is approximately 67% (Shergold, 1953), assuming maximum volume of single-size steel slag particles occupied the volume.

The actual expansion force due to unstable steel slag particles in a unit volume of concrete is

$$f_{eus} = \frac{F_{ec}}{V_{se}} = \frac{f_{ex} V_{sc}}{V_{sc} R \Phi} = \frac{f_{ex}}{R \Phi} \tag{12.20}$$

where f_{eus} is the expansion force of steel slag, which is generated by unstable slag particles in concrete, (N/m^3). Now, considering the expansion force from a single steel slag particle, (F_{ss}),

$$F_{ss} = f_{eus} V_{ss} = \frac{f_{ex}\pi d^3}{6R\Phi} = \frac{F_{ex}\pi d^3}{6V_{sl}R\Phi} \tag{12.21}$$

where F_{ss} is the expansion force from a single steel slag particle, (N); V_{ss} is the volume of the single steel slag aggregate particle, ((πd^3)/6) (m^3); and d is the nominal particle size of the steel slag aggregate, (m). The equation is illegal when $R=0$; that is, when the steel slag particles are volumetric stable (disruption ratio is zero) or the aggregate is natural aggregate (disruption ratio is zero).

How F_{ss} is distributed on the single particle and how to convert the plane stress F_{ss} to the dangerous stress in a particular use will be discussed in Section 12.3.

12.2.4 Laboratory experimental study

Preliminary laboratory testing has been conducted to verify (i) the maximum expansion force generated by bulk slag samples; (ii) the maximum expansion force generated by a single slag particle with a given particle size; (iii) the disruption ratios of different slag samples; and (iv) the volumetric stability of PCC containing these slag samples as a coarse aggregate. First of all, disruption ratio (R) tests were conducted.

12.2.4.1 Laboratory testing

Three steel slag samples and two air-cooled nickel slag samples were used in the preliminary expansion force test and autoclave disruption test. Basic oxygen furnace (BOF) steel slag samples BOF-1, BOF-2, and BOF-3 with nominal particle size of 20 mm (16–20 mm) have disruption ratios of 3%, 2%, and 5%, respectively, after an autoclave disruption test. Three steel slag samples were tested in the expansion force testing apparatus until the readings maintain stable. The range of chemical compositions of the slag samples is summarized in Table 12.1. Expansion forces determined for the steel slag samples are shown in Table 12.2. Expansion forces on single particles (N) are calculated based on Eq. (12.21).

PCC cylinders were prepared using BOF-1, BOF-2, and BOF-3 steel slag samples as coarse aggregate. As many research results indicated, the strength-related properties of the steel slag concrete are competitive to natural aggregate concrete. The volume stability has been excellent under 3 h of autoclave testing at 357 kPa, 137°C,

Table 12.1 **The range of chemical composition of the BOF slag samples (%)**

FeO	SiO	Al_2O_3	CaO	MnO	MgO	P_2O_5	Na_2O	S
21.5–28.1	12.7–18.1	2.4–3.0	35.1–40.6	4.0–4.5	8.8–11.3	0.51–0.74	0.07–0.14	0.08–0.12

Table 12.2 Expansion force readings for slag samples BOF-1, BOF-2, and BOF-3

	BOF-1		BOF-2		BOF-3	
Disruption ratio R (%)	3		2		5	
Nominal size (mm)	20		20		20	
Testing days	**Expansion force, F_{ex} (N)**	**Expansion force on a single particle (N)**	**Expansion force, F_{ex} (N)**	**Expansion force on a single particle (N)**	**Expansion force, F_{ex} (N)**	**Expansion force on a single particle (N)**
1	31	3	375	52	479	26
2	120	11	549	76	562	31
3	230	21	723	99	843	47
4	348	32	825	114	1120	62
5	472	43	1011	140	1394	77
6	510	47	1329	183	1780	98
7	652	60	1665	230	2146	119
8	1023	94	1971	272	3573	196
9	1464	135	2301	318	6680	369
10	1896	174	2637	364	9600	530
11	2430	224	3237	446	8500	470
12	2876	265	3573	493	10,650	588
13	3452	318	4023	556	13,680	756
14	4231	397	4023	556	15,884	878
15	4937	454	4021	555	18,054	998
16	5830	536			20,049	1109
17	6240	574			22,870	1265
18	7420	682			23,560	1303
19	8754	806			25,500	1410
20	8751	805			26,780	1481
23					28,994	1603
26					29,100	1609

for the concrete specimens containing BOF-1 and BOF-2 samples. The concrete specimens containing BOF-3 slag indicated surface popout although the autoclave testing result is marginally acceptable. Fig. 12.11 shows a concrete slice containing BOF-2 slag after 3 h of autoclave testing at 357 kPa, 137°C. It is at ~25 years of age.

Two nickel slag samples from a ferronickel smelter were tested to check the disruption ratio. The nominal particle size of the nickel slag is 25 mm. The samples were spitted into two fractions. From the results presented in Table 12.3, the disruption ratios for all samples are zero. Because Eq. (12.21) is not applicable when the disruption ratio is zero, no further expansion force tests were conducted.

PCC cylinders were prepared using nickel slag samples as the coarse aggregate of concrete. The concrete specimens have shown high strength and acceptable volumetric stability. Fig. 12.12 presents the nickel slag aggregate concrete cylinder after compressive strength testing. The mix proportions of the concrete are presented in Table 12.4 (Fig. 12.12).

12.2.4.2 Discussion

From Table 12.2, it can be seen that the maximum expansion force generated from single steel slag particles for BOF-1, BOF-2, and BOF-3 are 806, 556, and 1609 N, respectively. The expansion forces generated from BOF-1 and BOF-2 did not cause concrete specimens to disrupt and exhibit unacceptable surface distress under rigorous autoclave testing conditions. However, the concrete containing BOF-3 sample with

Fig. 12.11 Concrete containing steel slag coarse aggregate after autoclave testing.

Table 12.3 Disruption test results of nickel slag aggregates

	NS-1	NS-2
Nominal size (mm)	25	25
Disruption ratio R (%) (13.2–25 mm)	0	0
Disruption ratio R (%) (9.5–13.2 mm)	0	0

Fig. 12.12 Concrete containing nickel slag aggregate after compressive strength testing.

Table 12.4 Mix proposition of the concrete containing steel/nickel slag coarse aggregate

Proportions by weight (kg/m^3)				Mix ratio
W/C	Cement	Sand	Crushed slag	
0.47	368	619	1403	1:1.68:3.81

maximum expansion force 1609 N of single particle showed surface popout, which is unacceptable. There must be an inherent relationship between the allowable stress of rigid matrix, such as Portland cement mortar, and the maximum stress of a steel slag particle that is volumetrically unstable.

The autoclave disruption test can be used as the first step to evaluate if a steel slag or nonferrous slag, nickel slag, for instance in this study, is suitable to be used in confined matrices. If the autoclave disruption ratio is zero, in the cases of natural aggregates or volumetrically stable slags, no further expansion force testing is required, and that aggregate can be considered for use in confined conditions if all other technical requirements for that use are met. If the autoclave disruption ratio is not zero, further expansion force testing is required. The suitability for a special slag use in a confined condition depends on the maximum expansion force, the calculated tensile stress of a single slag particle, and the safest or allowable stress of the matrix in which the slag is used. Based on the analysis, preliminary laboratory testing, and comparison, the maximum expansion force is useful to evaluate and decide if a given steel slag is suitable for use in a given matrix with a constrained stress. Further work discussed in Section 12.3 includes (i) development of disruption modeling of concrete failure due to one single unstable steel slag particle to find the safety factor to relate the slag expansion force and plane stress and the allowable stress of the matrix; (ii) design and fabrication of a movable expansion force testing apparatus, which is convenient for use in the field and laboratory; (iii) development of possible inert fillers to be used in the compacted steel slag samples during the expansion force testing; and (iv) development of usability criteria. Even though there is some positive stability- and strength-related results for steel slag concrete samples, each specific slag should be fully quantified and checked for each specific use as there are limited quantitative guidelines. Although the concrete containing the slag samples showed acceptable stability, it is necessary to confirm this through detailed durability testing of the concrete incorporating a specific slag. At this stage, it is imperative that only special quality slag, of clearly proven suitability, is considered for concrete aggregate and confined application uses. These concrete applications should be nonstructural concrete, such as curb-and-gutter, valley gutter, barriers, islands, and sound walls.

12.3 Usability criterion development

Currently it is common for steel slag to be used as an unbound granular material, HMA aggregate, or other unbound uses. Although much of the research work conducted shows that properly aged steel slag can be nonexpansive when used in PCC and most researchers expressed optimistic views and envision the use of steel slag in concrete in the near future to enter the construction market based on their thorough laboratory and field research studies, the use in real projects are limited (Anastasiou & Papayianni, 2006; Fronek, 2011; Fronek et al., 2012; Kawamura, Torii, Hasaba, Nicho, & Oda, 1983; Moon, Yoo, & Kim, 2002; Nadeem & Pofale, 2012).

Many cases have shown success using air-cooled blast furnace slag (ACBFS) in concrete applications (eg, concrete pavement). The experience indicated it is essential that engineers and contractors who use ACBFS aggregates in concrete understand the unique properties of the slag to make sure that proper quality control measures are implemented and the expected performance of the end product is achieved (Hiraskar & Patil, 2013; Jahangirnejad et al., 2013).

This criterion is setup based on some basic concepts and assumptions, theoretical calculations, and modeling, such as the concept and calculation of the resultant expansion force produced by a mass of steel slag, the corresponding expansion force of the steel slag, the expansion force generated by a single slag particle, and a disruption model for steel slag particles in rigid matrixes. The experimental determination and calculation of the expansion force, which is the preparation for the establishment of the usability criterion, has been discussed in previous sections. The slag particle and disruption model established, which leads to the criterion, is discussed in this section.

12.3.1 Usability criterion deduction

The reasons for the limitation of steel slag in concrete arise mainly from two issues: one is the variation of volume stability of steel slag per se (some concrete containing steel slag aggregate might disrupt due to volume expansion of steel slag particles); and the other is that there have been no criteria developed to date to prove the relation between the expansion property of steel slag and the stability of concrete containing steel slag. Note that, however, from laboratory tests and field trials, some steel slag does show sufficiently stable to be used in cement concrete without making the concrete disrupt, even under rigorous treating conditions.

In Section 12.2, four questions are raised:

1. What degree of stability is needed for steel slag use as an aggregate in concrete?
2. How does one measure the stability or expansion of steel slag aggregate for use in concrete or other rigid matrix?
3. What is the approximate disrupture model of steel slag in concrete that can be used to estimate the feasibility of use?
4. How does one establish the relationship between the steel slag expansion characteristics and the constraining ability of the matrix in which steel slag acts as an aggregate?

Question 2 has been answered in Section 12.2.1 and Eq. (12.21) has been deduced as follows, which gives the expansion force from a single steel slag particle.

$$F_{ss} = f_{eus}V_{ss} = \frac{f_{ex}\pi d^3}{6R\Phi} = \frac{F_{ex}\pi d^3}{6V_{sl}R\Phi} \tag{12.22}$$

where F_{ss} is the expansion force from a single steel slag particle, (N); V_{ss} is the volume of the single steel slag aggregate particle, $((\pi d^3)/6)$ (m^3); and d is the nominal particle size of the steel slag aggregate, (m). The equation is illegal when $R=0$; that is, when the steel slag particles are volumetric stable (disruption ratio is zero) or the aggregate is natural aggregate (disruption ratio is zero).

Other questions will be answered in this section below.

It is known that concrete is a structurally sensitive material. An individual fracture will be regarded as failure of the structure. This is to say one single aggregate particle can cause the failure of the concrete structure. This is illustrated by Fig. 12.13. Only the unstable steel slag particle(s) contributes the instability of the structure. Fig. 12.13 on the left shows one unstable slag particle that can cause damage of the concrete

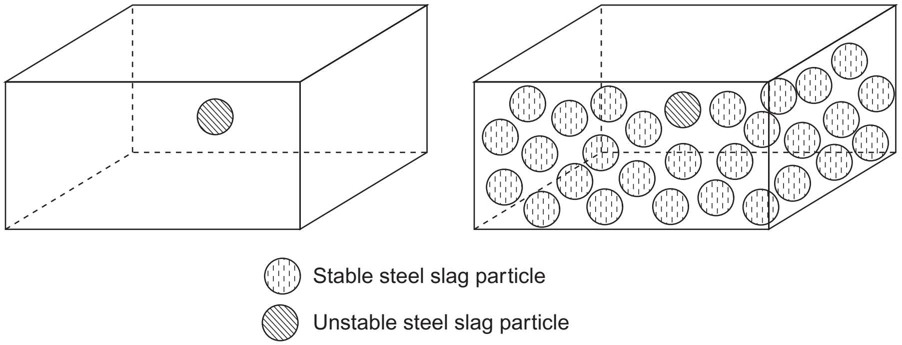

Fig. 12.13 Stable and unstable slag particles in rigid matrix.

matrix; the right side of Fig. 12.13 shows that when the same unstable particle is used with stable particles damage to the concrete may also be caused. The stability is controlled by the unstable particle. The unstable particles can be found by the rigorous autoclave disruption testing showed in Section 12.2.2.2. Most steel slag particle are stable under a severe autoclave testing. It has been reasonably assumed that only those unstable particles identified by the autoclave testing contributed expansion force, and the expansion force generated by one single particle can be determined by expansion force testing and calculation.

Therefore, the key problems to be solved are (i) how is the force distributed? And (ii) how can the criterion be established?

12.3.1.1 Disruption model for steel slag aggregate concrete

Consider the disruption of two different concretes: an ordinary concrete that has undergone external loading and a steel slag concrete that may fail due to a steel slag particle expansion. For ordinary aggregate concrete, due to an external force acting, the strength of concrete depends on the strength of the paste, the strength of the coarse aggregate, and the strength of the paste–aggregate interface. There is considerable evidence to indicate that this interface is the weakest region of concrete. In general, bond failures occur before failure of either the paste or the aggregate. Bond forces are partly due to van der Waals forces. However, the shape and surface texture of the coarse aggregate are important, as there may be a considerable amount of mechanical interlocking between the mortar and the coarse aggregate. Flexural and tensile strength of concrete made with rough aggregate may be up to 30% higher than concrete made with smooth aggregate. In addition, although the aggregate is usually considered to be chemically inert, there may be some strength-contributing chemical reactions between the cement and the aggregate.

However, the situation for steel slag aggregate concrete undergoing failure due to expansion of the steel slag is different from that for ordinary concrete loaded by an external force. The difference is that the force causing failure results from the internal expansion force of the concrete (steel slag) and not from external forces (ignoring the effect of external force at present).

Before setting up a model for disruption in steel slag concrete, it is necessary to consider an important point: concrete is a structurally sensitive material, which means that, for failure to be deemed to have occurred, it is not necessary for concrete to disrupt catastrophically until complete failure. On the contrary, only one localized failure can result in overall failure of the concrete. This is why the basic model for disruption of steel slag concrete derived later is based on one steel slag particle.

For ordinary aggregate concrete, the failure of concrete is initiated from separation of the interface between the mortar and aggregate surface (mainly due to tension and shear), resulting in propagation of cracks in the mortar. For the case of a steel slag particle and mortar, the failure is considered to be mainly the result of tension in the mortar due to the expansion of steel slag. If the tensile strength of the mortar matrix is greater than the tensile stress exerted on the mortar, due to the expansion of steel slag, at all ages during the performance of the concrete in service, failure will not occur due to expansion of the steel slag. On the contrary, the boundary region between the slag aggregate and mortar will be strengthened if there is a slight expansion, which will contribute to strength gains in addition to van der Waals forces and chemical reaction and play a role of “prestressing.” It is considered that this is one of the reasons why steel slag concrete has much higher strength than ordinary aggregate concrete.

12.3.1.2 Usability criterion for steel slag in concrete

Incorporating the material presented previously, it is possible to derive the usability criterion shown as follows.

Before discussion of the criterion, four simplifying assumptions are made:

- **(i)** Steel slag aggregate particle is spherical.
- **(ii)** Not every slag particle is expansive; the percentage of cracked particles is *R* (from the autoclave test); and the expansion force is contributed only by the particles that crack.
- **(iii)** Steel slag aggregate with single particle size is used (for simplification of the basic model).
- **(iv)** Steel slag particle breakage might result in the breaking of mortar matrix (from the structural sensitivity property).

The aggregate tensile splitting force is produced from the resultant force of normal volume stress, and can be obtained by integrating the expansion force per unit volume in the volume of the half particle (Fig. 12.14):

$$P_{\mathrm{t}} = \sigma_{euv} \iiint\limits_{V} dv = \sigma_{euv} \int_0^{\pi} \sin\theta \sin\theta \, d\theta \int_0^{\pi} d\varphi \int_0^{d/2} r^2 dr = \tfrac{\pi^2 d^3}{48} \sigma_{euv} \tag{12.23}$$

or

$$P_{\mathrm{t}} = \frac{\pi^2 d^3 \sigma_{\mathrm{e}}}{48 R \Phi} \tag{12.24}$$

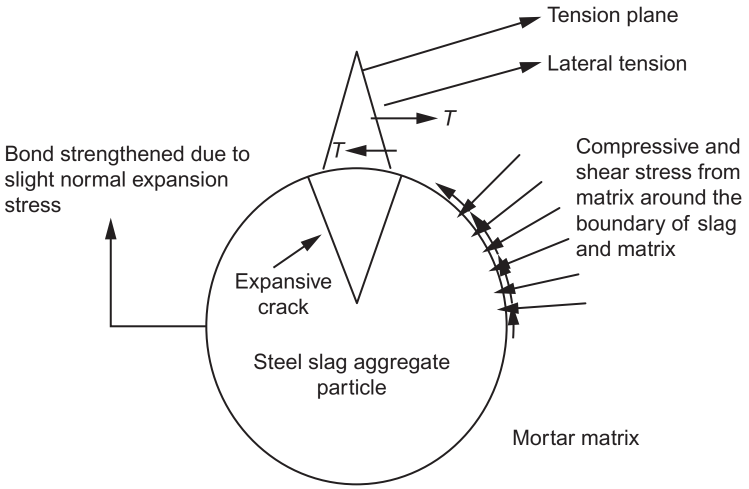

Fig. 12.14 The mechanical disruption modeling of expansive slag particle.

The tension stress (at) acts on the diametrical section of the steel slag particle and is given by

$$\sigma_\mathrm{t} = \frac{P_\mathrm{t}}{A_\mathrm{ms}} = \frac{\pi d \sigma_\mathrm{e}}{12R\Phi} \tag{12.25}$$

where A_ms is the area on a diameter of a steel slag particle.

This force will produce a normal compressive stress in the mortar matrix under uniform expansion condition. The normal stress acting on the surface of the steel slag particle is

$$\sigma_\mathrm{n} = \frac{P_\mathrm{es}}{A_\mathrm{s}} = \frac{\sigma_\mathrm{e} d}{6R\Phi} \tag{12.26}$$

where A_s is the whole surface area of a steel slag particle, (πd^2).

It can be seen that the tensile stress, σ_t, is larger than the normal stress, σ_n. Therefore the dangerous (maximum allowable) stress is governed by the tension stress σ_t, as in Eq. (12.25).

$$\sigma_\mathrm{d} = k\sigma_\mathrm{t} \le [\sigma], \quad \text{ie} \tag{12.27}$$

$$\sigma_\mathrm{d} = k\frac{\pi d \sigma_\mathrm{e}}{12R\Phi} \le [\sigma] \tag{12.28}$$

This is the usability criterion for steel slag use in cement-based matrix materials, where σ_n is the dangerous stress and [σ] is the allowable tensile stress of the matrix (cement mortar in this case).

12.3.1.3 Determination of expansion force of steel slag

As shown in Eq. (*12.27*), a criterion has been deduced for the establishment of the relationship between expansion force per unit volume (three-dimensional force) and the allowable stress (two-dimensional stress) of the stiff matrix where steel slag would probably be used.

Essentially, a usability criterion for steel slag used in stiff (nonplastic) matrix has been established. Obviously, this criterion can be extended to other types of slag aggregates that are prone to volume expansion or the utilization of steel slag in another rigid matrix or semirigid matrix, such as asphaltic concrete under low temperatures.

The deduction of the equation is based on the disruption model and theoretical analysis. Therefore another factor, which has to be addressed to enable the criterion to be used in practice, is how to determine the expansion stress, σ_e, of the compacted mass of steel slag by laboratory experiment to prove the accuracy of the equation.

12.3.2 Experimental verification

Due to the relatively slow hydrating procedure of steel slag, the 74 ± 3°C water soaking accelerated test was adopted, as described previously.

The slag was placed in the mold with perforated base plates to allow for moisture movement during the immersion period. The diameter of the mold was 150 mm, the area 17,600 mm, and the height of the section containing materials was 128 mm; therefore, the volume of contained materials was 2.26×10^6 mm^3. The mold was then totally immersed in a container filled with water maintained at 74 ± 3°C. A spacer disc was used and the steel slag was compacted in three layers with 56 blows per layer. The container was put on the base platen of a stiff testing machine. A sensitive load cell was inserted between the mold and the top platen of the testing machine. At the commencement of the test an initial preload (on the load cell) of approximately 10 N was applied to ensure that there was sufficient support force between the top of the machine and the mold. Because evaporation of the hot water takes place, it was found necessary to oil the surface of the top platen of the machine and the load cell to reduce the possibility of corrosion. Water was added daily to compensate for the water evaporated.

Load cell readings were taken every 24 h. The reading from the load cell in Newtons can be converted to the expansion force P_e; from Eq. (*12.27*), the dangerous maximum allowable stress can be calculated and if the allowable tensile tress of the Portland cement used is known, comparison can be made based on the equation. Typical results of an expansion test and relevant calculation are given in the example below.

Example: BOS slag from a steelworks has a particle size of 20 mm, and its particle-cracking ratio is 3% as determined by autoclaving. Values of expansion force determined for the steel slag are shown in Table 12.5.

Now, suppose that it is planned to use the steel slag as an aggregate in PCC and that the cement to be used is Type A, which has an allowable tension stress of 2, 3.2, and 4.5 MPa at 3, 7, and 28 days, respectively. Assuming a factor of safety (k) of 1.5, is it possible to use this slag in the concrete?

As stated in Section 12.2.1, the resultant expansion force is six times the readings in Table 12.5; that is, $P_e = 6T$ (Eq. *12.15*), where T is the expansion force acting on the top surface of the sample (dial gauge reading).

At 28 days, the dangerous stress is given by

$$\sigma_d = k\frac{\pi d\sigma_e}{12R\Phi} = \frac{1.5\times\pi\times0.02\times8750\times6\times10^6}{12\times0.03\times0.67\times2260} = 9.07\,\text{MPa} > [\sigma] = 4.5\,\text{MPa}$$

Therefore, the given steel slag cannot be used in concrete.

As we know, if the steel slag is to be used in cement matrix, the dangerous stress produced from the expansion stress of the steel slag at each age should be less than the allowable stress of Portland cement at the corresponding age. If this situation exists, then we can say that the utilization of the steel slag as a coarse aggregate in the cement matrix is safe.

Table 12.5 Expansion reading from dial gauge for the sample

Age	1 day	2 days	3 days	4 days	5 days	6 days	7 days
Expansion force (N)	30	120	230	348	472	510	654
Age	8 days	9 days	10 days	11 days	12 days	13 days	14 days
Expansion force (N)	789	1023	1460	1896	2430	2876	3452
Age	15 days	16 days	17 days	18 days	19 days	20 days	21 days
Expansion force (N)	4231	4937	5830	6240	7420	8754	8750

12.3.2.1 Experimental results

At 24-h intervals, readings were taken from the display for the load cell. The real expansion force, P_e (Eq. *12.15*), should be calculated by deducting the 0 day reading (initial reading) and adding the force due to the mass of the top plate and surcharge; that is,

$$P_e = 6\times(D - I + S) \tag{12.29}$$

where P_e is expansion force for compacted mass of steel slag space (or apparent volume expansion force); D is reading from load cell; I is initial reading; and S is surcharge of steel slag sample (45.6 N).

A 16 mm steel slag aggregate was used for the preliminary testing. The expansion stress and the corresponding linear expansion of the slag is shown in Table 12.6.

12.3.2.2 Calculation

From Table 12.6, the maximum expansion force occurred at 13 days (ie, 4,023.6 N).

The dangerous stress is given by Eq. (12.26).

$$\sigma_d = k\frac{\pi d\sigma_e}{12R\Phi} = \frac{1.5\pi\times 0.016\times 4023.6\times 10^6}{12\times 0.03\times 0.67\times 2260} = 0.56\text{MPa} < [\sigma] = 3.2\text{MPa}$$

Table 12.6 **Results of expansion force test.**

Test days	Reading (N)	Total expansion force P_e (N)	Expansion force per unit volume, σ_e ($\times 10^4$ N/m^3)	Corresponding free volume expansion (%)
1	17	375.6	16.6	0.15
2	46	549.6	24.3	0.36
3	75	723.6	32.0	0.54
4	92	825.6	36.5	0.69
5	123	1011.6	44.8	0.86
6	176	1329.6	58.8	1.00
7	232	1665.6	73.7	1.13
8	283	1971.6	87.2	1.35
9	338	2301.6	101.8	1.48
10	394	2637.6	116.7	1.59
11	494	3237.6	143.3	1.71
12	550	3573.6	158.1	1.85
13	625	4023.6	178.0	1.95
14	543	3531.6	156.3	2.02
15	602	3885.6	171.9	2.10
16	582	3765.6	166.6	2.16
17	480	3153.6	139.5	2.21
18	512	3345.6	148.0	2.25

σ_e is obtained from P_e divided by volume of steel slag tested (2.26×10^6 mm^3).

The dangerous stress is less that the allowable stress of Type I Portland cement at 7 days; therefore, the steel slag is acceptable to be used in the cement matrix.

The comprehensive criterion for the use of BOF slag as an aggregate in concrete is established based upon four basic steps: experimental determination of expansion stress; calculation of expansion stress; disruption model of steel slag in concrete; and theoretical development of criterion.

From theoretical analysis and experiments, it can be concluded that the maximum expansion stress, as discussed above, is useful and reliable for evaluating if a given steel slag is suitable for use in a given matrix with a constrained stress. The concrete made with the steel slag aggregate conforming to the criterion deduced in this paper is volumetrically stable under both the autoclave test and water soaking for long-term curing. The author proposes that steel slag having acceptable stability can be used in nonstructural concrete applications after field trials including nonreinforced sidewalk and pavement, curb, curb-and-gutter, expressway gutter, valley gutter, and other nonstructural concrete placements, concrete highway pavements, runway pavements, and so on.

To simplify the calculation of the surface area of a steel slag particle, a spherical shape is assumed and the nominal particle size is used for the diameter of the spherical shape of a steel slag particle. Therefore, the surface area is πd^2. Hence the surface tensile stress generated by the three steel slag samples in Table 12.2 are 0.64, 0.57, and 1.21 MPa, respectively. If the stress distribution is correct, what is the relationship between the surface tension stress and the tensile strength of Portland cement mortar (approximately 3 MPa)? If the assumption on the stress is not correct, how is the expansion force distributed on a single slag particle? If these questions can be solved, usability criteria can be established for steel slag aggregate use in bound or rigid matrices.

The expansion force test and disruption ratio test can be used jointly or separately to evaluate the expansive properties of steel slag and other nonferrous slag aggregates, especially when the slag is used as coarse aggregates under confined conditions. The equations deduced can convert the expansion force of bulk slag sample to the expansion force of a single slag particle that can be used to establish usability criteria based on appropriate disruption modeling(s) of steel slag in confined conditions. The maximum expansion forces generated by the three slag samples are 806, 556, and 1609 N. The corresponding surface tension stresses are 0.64, 0.57, and 1.21 MPa, respectively. Based on a visual observation on the concrete specimens containing the three slag samples after rigorous autoclave testing and the expansion forces and tension stresses of the steel slag samples, usability criteria for the use of coarse steel slag in concrete can be established based on the steel slag concrete disruption model.

12.3.3 Portable expansion force testing device development

From Section 12.2.2.1, although the principles and results are reliable, it is obvious that using a universal testing machine for the expansion force test is not practical, as the test occupies the testing machine for several weeks, and only one sample can be tested at a time. Therefore, a portable expansion force testing apparatus needs to be designed and fabricated. Fig. 12.15 presents the embryonic form of the portable

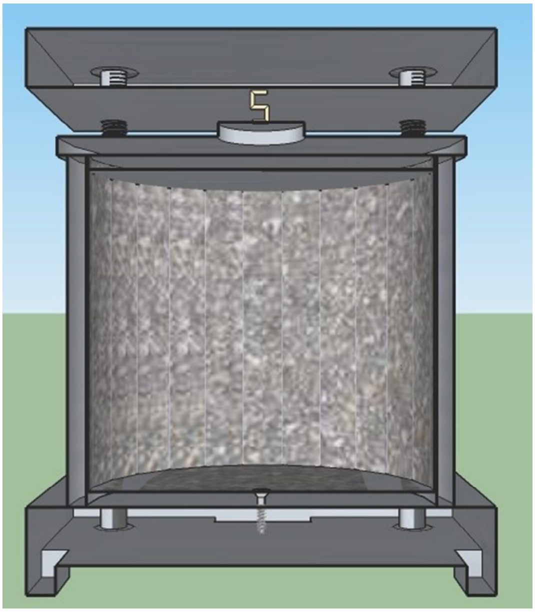

Fig. 12.15 The embryonic form of the portable expansion force testing apparatus to be developed.

expansion force testing apparatus that is being developed. Perforated mode is selected. This device simulates the trial expansion testing presented in Section 12.2.2.1 (Figs. 12.7 and 12.8). Compared to the universal testing machine used, the portable device can be used in both the field and the laboratory and can run parallel slag aggregates simultaneously.

12.4 Summary

Apparently, most concerns with the use of steel slag in cement concrete as coarse or fine aggregate result from the expansion of steel slag.

Experiments have shown that the usability criterion is reliable and volumetric expansion stress is useful for evaluating whether a given steel slag is suitable for use in a given rigid matrix with a constrained stress.

It is possible to establish a quantitative relationship between slag and individual end products. For slag use in nonrestrained and restrained conditions or rigid matrixes the control parameters should be different.

Laboratory volume expansion testing conducted with comparison of the results of theoretical volume expansion proved that they correlated well. Furthermore, it has been experimentally proven that certain volume expansion of steel slag can be absorbed internally by the void volume in bulk steel slag under external surcharge weight making the apparent volume expansion equal zero. The minimum (lowest) absorbable void volume is approximately 7.5%, which is unrelated to the free lime content. The usability criterion is developed based on the volume expansion of steel slag (%) and the minimum percentage of the volume that can take the volume expansion of steel slag (%). Eventually the criterion (relationship) is established based on the free lime content, the specific gravity, and bulk-relative gravity of a specific steel slag sample. The criteria is the potential to be used as guidance and prediction for the use of steel slag and other expansion-prone nonferrous slags (copper, nickel, for instance) as a granular material in highway construction.

The tensile stress of a single steel slag developed can be used to quantitatively evaluate the stability of steel slag and related to the tensile stress of cement mortar matrix. Based on the results, the inherent relationship between the expansion force of steel slag and the allowable stress of a rigid matrix exists and can be revealed. Usability criterion for the use of steel slag under confined conditions can be further developed.

Questions

12.1 Why can expansion force, not volumetric expansion, better assess the usability of steel slag used in concrete?
12.2 Which two tests are needed to determine the expansion force on single steel slag particles?
12.3 How to use the expansion force on a single particle to deduce the usability criterion?
12.4 How does slag affect the performance of end products? Use one example to explain.
12.5 What are the differences between the uses in restrained and nonrestrained conditions?
12.6 Why does the expansion force produced by a slag aggregate need to be determined when it is used in a rigid matrix?
12.7 Can the expansion force generated from a single slag particle be determined solely by testing?
12.8 How do you use the expansion force from a single slag particle to relate the strength of a matrix material?

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Slag use in cement manufacture and cementitious applications

13

13.1 Introduction

Portland cement (hydraulic cement) is the major ingredient in concrete. Most practically, Portland cement is used globally to make concrete structural, nonstructural, or functional components for all kinds of constructed facilities including buildings, bridges, roads, runways, sidewalks, and dams. Cement is indispensable for construction activity, so it is tightly linked to the global economy. In 2014, more than 3.5 billion tonnes (3.85 billion tons) of Portland cement were consumed worldwide, with 89 million tonnes (97.9 million tons) consumed in the United States (USGS, 2015). Cement production is growing by 2.5% annually, and it is expected to rise from 3.5 billion tonnes in 2014 to around 4.5 billion tonnes (4.95 billion tons) by 2030.

During the calcination operation in the manufacture of Portland cement clinker, calcium combines with the other components of the raw materials to form four principal compounds that make up 90% of cement by mass. Gypsum or other calcium sulfate source, and grinding aids, are added during grinding.

Although elements are reported in chemical composition as simple oxides for standard consistency, they are usually not found in oxide form in Portland cement. The amount of calcium, silica, and alumina establish the amounts of the primary compounds (minerals) in the cement and effectively affect the properties of hydrated cement. Sulfate is present to control setting, as well as drying, shrinkage, and strength gain.

The following chemical abbreviations are normally used to describe compounds:

$A = Al_2O_3$, $C = CaO$, $F = Fe_2O_3$, $H = H_2O$, $M = MgO$, $S = SiO_2$, and $\overline{S} = SO_3$.

There are four primary compounds in Portland cement, their approximate chemical formulas, and abbreviations are expressed as

Tricalcium silicate $3CaO{\cdot}SiO_2 = C_3S$
Dicalcium silicate $2CaO{\cdot}SiO_2 = C_2S$
Tricalcium aluminate $3CaO{\cdot}Al_2O_3 = C_3A$
Tetracalcium aluminoferrite $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3 = C_4AF$

The forms of calcium sulfate, their chemical formulas, and abbreviations are

Anhydrous calcium sulfate $CaSO_4 = CaO \cdot SO_3 = C\overline{S}$
Calcium sulfate dihydrate (gypsum) $CaSO_4 \cdot 2H_2O = CaO \cdot SO_3 \cdot 2H_2O = C\overline{S}H_2$
Calcium sulfate hemihydrate $CaSO_4 \cdot 1/2H_2O = CaO \cdot SO_3 \cdot 1/2H_2O = C\overline{S}H_{1/2}$
Gypsum, calcium sulfate dihydrate, is the predominant source of sulfate used in cement.

The Utilization of Slag in Civil Infrastructure Construction. http://dx.doi.org/10.1016/B978-0-08-100381-7.00013-6

C_3S and C_2S in clinker are also referred to as alite and belite, respectively. Alite constitutes 50–70% of the clinker, whereas belite accounts for 15–30%. Aluminate compounds constitute about 5–10% of the clinker and ferrite compounds 5–15% (Hewlett, 1998).

The primary cement compounds have the following properties:

> Tricalcium silicate hydrates and hardens rapidly and is largely responsible for initial set and early strength. In general, the early strength of Portland cement concrete is higher with increased percentages of C_3S.
>
> Dicalcium silicate hydrates and hardens slowly and contributes largely to strength increase at ages beyond 1 week.
>
> Tricalcium aluminate liberates a large amount of heat during the first few days of hydration and hardening. It also contributes slightly to early strength development. Cements with low percentages of C_3A are more resistant to soils and waters containing sulfates.
>
> Tetracalcium aluminoferrite is the product resulting from the use of iron and aluminum raw materials to reduce the clinkering temperature during cement manufacture. It contributes little to strength. Most color effects that make cement gray are due to C_4AF and its hydrates.
>
> Calcium sulfate, as anhydrous calcium sulfate, gypsum (calcium sulfate dihydrate or hemihydrate), is added to cement during final grinding to provide sulfate to react with C_3A to form ettringite (calcium trisulfoaluminate). This controls the hydration of C_3A. Without sulfate, a cement would set rapidly. In addition to controlling setting and early strength gain, the sulfate also helps control drying shrinkage and can influence strength through 28 days (PCA, 2003).

When they react with water, these compounds hydrate to form new compounds that are the infrastructure of hardened cement paste in concrete. The calcium silicates, C_3S and C_2S, hydrate to form the compounds calcium hydroxide and calcium silicate hydrate (tobermorite gel). Hydrated Portland cement contains 15–25% calcium hydroxide and about 50% calcium silicate hydrate (CSH) by mass. The strength and other properties of hydrated cement are due primarily to CSH. C_3A reacts with water and calcium hydroxide to form tetracalcium aluminate hydrates. C_4AF reacts with water to form calcium aluminoferrite hydrates. C_3A, sulfates (gypsum, anhydrite, or other sulfate source), and water combine to form ettringite (calcium trisulfoaluminate hydrate), calcium monosulfoaluminate, and other related compounds (Lea, 1970).

The approximate percentage of each compound can be calculated from a chemical oxide analysis (ASTM C114 or AASHTO T105) of the unhydrated cement per ASTM C150 or AASHTO M85 (Bogue calculations). X-ray diffraction (XRD) techniques can also be used to more accurately determine compound percentages as per ASTM C 1365.

The phases in Portland cement must chemically react with water to develop strength. The amount of water added to a mixture controls the durability as well. The space initially taken up by water in a mixture is partially or completely replaced over time as the hydration reactions proceed. Theoretically, if more than 35% water (a water-to-cement (W/C) ratio of 0.35) is used, the porosity (capillary porosity) in the hardened material will remain, even after complete hydration. As the W/C ratio increases, the capillary porosity increases, and the strength decreases.

For complete hydration of Portland cement, only about 40% water is needed. If a W/C ratio greater than about 0.40 is used, the excess water not needed for cement hydration remains in the capillary pores or evaporates. If a W/C ratio less than about 0.40 is used, some cement particles will remain unhydrated.

13.1.1 Types of cement

ASTM C150 specifies five types of Portland cement; ASTM C595 or C1157 specifies eight types of blended hydraulic cement; ASTM C91 specifies three types of masonry cement, two types of plastic cement, three types of expansive cement, and a number of special Portland or blended cements for block, pipe, prestressed heat-cured concrete, and other product applications.

Table 13.1 shows the chemical compound of the five types of Portland cement. Types I, II, and III are normally readily available in all local market areas.

Table 13.1 Typical compound composition of Portland cements

Cement type	Compound (%)							
	C_3S	C_2S	C_3A	C_4AF	MgO	SO_3	Ignition loss	Free CaO
I	55	19	10	7	2.8	2.9	1.0	1.0
II	51	24	6	11	2.9	2.5	0.8	1.0
III	57	19	10	7	3.0	3.1	0.9	1.3
IV	28	49	4	12	1.8	1.9	0.9	0.8
V	38	43	4	9	1.9	1.8	0.9	0.8

Data from Dobrowolski, J.A. (1998). *Concrete construction handbook* (4th ed.). New York, NY: McGraw-Hill.

Type I cement is generally supplied unless another type is specified. It frequently meets Type II specifications.

Type II has moderate sulfate resistance, with or without moderate heat of hydration (modified). Modified is used when optional additional requirements are invoked such as moderate heat of hydration and low alkali. The maximum content of C_3A is 8%. This type of cement is specified in concrete exposed to seawater.

Type III is high early strength cement. It is produced by finer grinding of a clinker with a higher percentage of C_3A and C_3S. The gypsum level is increased slightly. Concrete using this cement has a 3-day compressive strength approximately equal to the 7-day compressive strength for Types I and II and a 7-day compressive strength almost equal to the 28-day compressive strength for Types I and II.

Type IV is low heat cement. Percentages of C_2S and C_4AF are relatively high, while C_3A and C_3S are low compared to other types. Heat of hydration is less than for other types, and the heat develops more slowly. Strength development is much slower, but after 1–2 years is higher than other cements if curing is continued. This cement is used for massive concrete structures with low surface/volume ratios. It is available only on special order for very large tonnages with long lead times, if at all. It requires much longer and more careful curing than other types.

Type V is sulfate resistant. It has a very low C_3A content ($\leq$ 5% maximum). This type is used in concrete exposed to alkali soil-borne sulfates and groundwater sulfates (Dobrowolski, 1998).

13.2 Raw materials of Portland cement and end product requirements

The manufacture of Portland cement includes four steps: (i) winning virgin raw materials, including limestone and clay, normally from a quarry located near the cement manufacturing plant; (ii) conducting chemical and mineral analyses of the materials, and proportion, blend, and grind them; (iii) heating (calcining) the raw materials in a cement kiln; and (iv) cooling the red-hot clinker and then grinding it with a small amount of gypsum. The end result is a fine, gray powder called Portland cement. The fineness of Portland cement can be such that 1 pound of cement powder contains 150 billion grains.

Portland cement is manufactured with one of the following processes: wet process, long dry process, dry process with preheater, or dry process with precalciner. The wet process is the oldest and most energy consumptive method. Modern plants are designed and constructed to be retrofitted to use the more energy-efficient dry processes of preheater or precalciner (PCA, 2003).

13.2.1 Mineral sources, material process, and property requirements

Portland cement is made primarily from a calcareous material, such as limestone or chalk, and from alumina and silica found as clay or shale. Marl, a mixture of calcareous and argillaceous materials, is also used. Raw materials for the manufacture of Portland cement are found in nearly all countries, and cement plants operate all over the world. The process of manufacturing cement consists essentially of grinding the raw materials, mixing them intimately in certain proportions, and burning in a large rotary kiln at a temperature of up to about 1450°C (2642°F) when the material sinters and partially fuses into balls known as *clinker*. The clinker is cooled and ground to a fine powder, with some gypsum added, and the resulting product is commercial Portland cement. Details of the dry process of the manufacture of cement are given in Fig. 13.1.

In the semidry or dry processes, the mixing and grinding of the raw materials is done in a semidry or dry condition. In the wet process, the material is in a slurry state. The selection of dry or wet methods depends on the hardness of the raw materials used and on their moisture content.

In the dry and semidry processes, the raw materials are crushed and fed in the correct proportions into a grinding mill, where they are dried and reduced in size to a fine powder. The dry powder (raw meal), is pumped to a blending silo, and final adjustment is made in the proportions of the materials required for the manufacture of cement. To obtain a uniform and intimate mixture, the raw meal is blended, usually by means of compressed air inducing an upward movement of the powder and decreasing

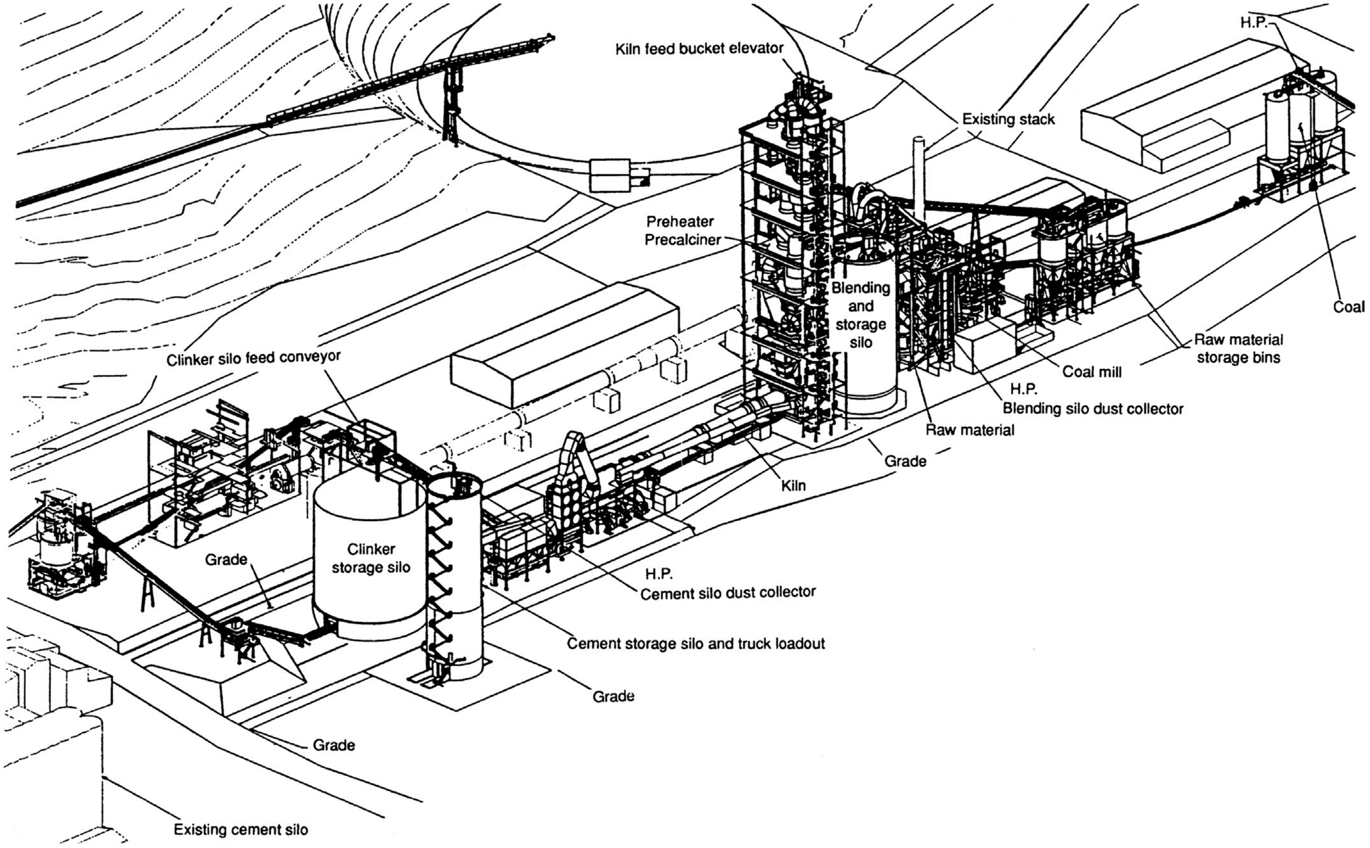

Fig. 13.1 Modern dry process of Portland cement manufacture.

its apparent density. The air is pumped over one quadrant of the silo at a time, and this permits the apparently heavier material from the nonaerated quadrants to move laterally into the aerated quadrant. Thus the aerated material tends to behave almost like a liquid and, by aerating all quadrants in turn for a total period of about 1 h, a uniform mixture is obtained. In some cement plants, continuous blending is used. In the semidry process, the blended meal is sieved and fed into a rotating dish called a granulator, water weighing about 12% of the meal being added at the same time. Hard pellets about 15 mm (0.6 in.) in diameter are formed. This is necessary, as cold powder fed directly into a kiln would not permit the airflow and exchange of heat necessary for the chemical reactions of formation of cement clinker.

The pellets are baked hard in a preheating grate by means of hot gases from the kiln. The pellets then enter the kiln. The amount of heat required is much lower because only some 12% of moisture has to be driven off, but additional heat has already been used in removing the original moisture content of the raw materials (usually 6–10%). The process is thus quite economical, but only when the raw materials are comparatively dry. In such a case the total coal consumption can be as little as 100 kg (220 lb) per tonne (ton) of cement.

In the dry process, the raw meal, which has a moisture content of about 0.2%, is passed through a preheater, usually of a suspension type; that means that the raw meal particles are suspended in the rising gases. Here, the raw meal is heated to about 800°C (1472°F) before being fed into the kiln. Because the raw meal contains no moisture to be driven off and because it is already preheated, the kiln can be shorter than in the wet process. The preheating uses the hot gas leaving the kiln. Because that gas contains a significant proportion of the rather volatile alkalis and chlorides, a part of the gas may need to be bled off to ensure that the alkali content of the cement is not too high.

The major part of the raw meal can be passed through a fluidized calciner (using a separate heat source) introduced between the preheater and the kiln. The temperature in the fluidized calciner is about 820°C (1508°F). This temperature is stable so that the calcination is uniform and the efficiency of the heat exchange is high.

A part of the raw meal is fed directly into the kiln in the usual manner but, overall, the effect of the fluidized calciner is to increase the decarbonation (dissociation of $CaCO_3$) of the raw meal prior to entry into the kiln and thus greatly to increase the kiln throughput. What is probably the largest dry-process plant in the world produces 10,000 tonnes (11,000 tons) of clinker a day using a kiln 6.2 m (20 ft) in diameter and 105 m (345 ft) long. This output of a single kiln is equal to approximately one-fifth of the cement consumption of the whole of the United Kingdom.

It should be stressed that all processes require an intimate mixture of the raw materials because a part of the reactions in the kiln must take place by diffusion in solid materials, and a uniform distribution of materials is essential to ensure a uniform product.

On exit from the kiln, regardless of the type of process, the clinker is cooled, the heat being used to preheat the combustion air. The cool clinker, which is characteristically black, glistening, and hard, is interground with gypsum to prevent flash setting of the cement. The grinding is done in a ball mill consisting of several compartments with progressively smaller steel balls, sometimes preceded by passing through a roll press. In most plants, a closed-circuit grinding system is used: the cement discharged by the mill is passed through a separator, fine particles being removed to the storage silo by an air current, while the coarser particles are passed through the mill once again. Closed-circuit grinding avoids the production of a large amount of excessively fine material or of a small amount of too coarse material, faults often encountered with open-circuit grinding. Small quantities of grinding aids such as ethylene glycol or propylene glycol are used. The performance of a ball mill can be improved by pregrinding the clinker in a horizontal impact crusher.

Once the cement has been satisfactorily ground, when it will have as many as 1.1×10^{12} particles per kg (5×10^{11} per lb), it is ready for transport in bulk. Less commonly, the cement is packed in bags or drums. However, some types of cement, such as white, hydrophobic, expansive, regulated-set, oil-well, and high-alumina, are always packed in bags or drums. A standard bag in the United Kingdom contains 50 kg (110 lb) of cement; a US sack weighs 94 lb (42.6 kg); other bag sizes are also used. Bags of 25 kg are becoming popular (Neville, 1996).

13.2.2 Environmental and energy aspects

Cement manufacturing is highly energy and emissions intensive because of the extreme heat required to produce it. Producing a tonne of cement requires 4.7 million British Thermal Units (Btus) of energy, equivalent to approximately 181 kg (400 lb) of coal, and generates nearly a tonne of CO_2. Given its high emissions and energy consumption, cement should obviously be given critical attention to use alternative recycled materials such as various slags to reduce greenhouse gas emissions and energy consumption.

The energy consumed in Portland cement manufacturing is used to crush, mix, burn, and grind the raw materials. In the meantime, greenhouse gases and dust are generated. Fossil fuel burning is the major source of greenhouse gases, specifically, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

The cement industry is ranked eighth among manufacturing sectors for energy use and emissions released. The cement industry has the highest energy intensity per dollar value of output of any manufacturing sector. The energy consumption per dollar value of shipments in Btus is 56.2, over twice that of the second-ranked iron and steel sector, with 27.8 Btus (Calkins, 2009).

The raw materials for cement contain varying contents of calcium oxide, silicon dioxide, aluminum oxide, and iron oxide. Because these contents vary, the mixture of raw materials differs among cement plants and locations. The total weight of inputs is greater than the Portland cement output, as a large percentage of the weight of limestone is released as CO_2 (Lippiatt, 2007).

In addition to CO_2 release and energy use, the mining of limestone, the major raw material in cement, can cause habitat destruction, increased runoff, and pollutant release to air and water. Some limestone mining operations are abandoning open-pit mining techniques in favor of underground mining. This technique may reduce some habitat and pollution impacts, yet may increase cost.

13.2.2.1 Emissions in cement production

The production of cement releases greenhouse gas emissions both directly and indirectly: the heating of limestone releases CO_2 directly, while the burning of fossil fuels to heat the kiln indirectly results in CO_2 emissions.

Worldwide, the cement sector is responsible for about 5% of all man-made emissions of CO_2, the primary greenhouse gas that drives global climate change. CO_2 emissions in the cement sector result from two causes: the chemical conversion from the calcination of limestone and other carbonate-containing feedstocks, and carbon-based fuel consumption. CO_2 from the chemical conversion is the second largest industrial (nonfuel-related) source of CO_2 in the United States, totaling 45.9 million tonnes in 2005. Nearly 50 million tonnes (55 million tons) were released the same year from fuel combustion for electricity and power to manufacturing equipment to produce cement. So, the total CO_2 is slightly less than 1 tonne of CO_2 released for each of the 99 million tonnes of cement produced in 2005. The nonfuel release of CO_2 accounts for about 29% of nonfuel-related CO_2 emissions from manufacturing, second only to the iron and steel industry, which accounts for about 37%.

The direct emissions of cement occur through *calcination*, the chemical process of production. Calcination occurs when limestone is heated, breaking down into calcium oxide and CO_2. This process accounts for ~50% of all emissions from cement production (Calkins, 2009).

Indirect emissions are produced by burning fossil fuels, usually coal, natural gas, or oil, to heat the kiln. The combustion of these fuels produces additional CO_2 emissions. This represents approximately 40% of cement emissions. The electricity used to power other plant machinery, and the final transportation of cement, represents another source of indirect emissions and account for 5–10% of the industry's emissions. Indirect emissions from burning fossil fuels to heat the kiln can be reduced by switching to alternative fuels, including natural gas, biomass, and waste-derived fuels such as tires, sewage sludge, and municipal solid waste. Reducing emissions from the calcination process means looking to a material other than limestone. Blended cement replaces some of the limestone-based clinker with other materials, primarily coal fly ash and blast furnace slag (BFS). Blended cement could reduce CO_2 emissions by as much as 20% (Rubenstein, 2012).

Alternatively, efficiency measures can reduce the demand for fuel by addressing the production process itself (such as switching from inefficient wet kilns to dry ones) or through technical and mechanical improvements (such as preventative maintenance to repair kiln leaks). While some estimate that energy efficiency improvements could achieve emission reductions of up to 40%, some industry analyses suggest that producers may have already exhausted this potential. Without additional financial incentives (such as subsidies or a tax on carbon), further breakthroughs could be difficult.

13.2.2.2 Energy use in cement production

The production of cement is an energy-intensive process using primarily fossil fuel sources. Cement comprises about 10% of a typical concrete mix but accounts for 92% of its energy demand. Cement production requires the pyroprocessing of large quantities of raw materials in large kilns at high and sustained temperatures to produce clinker. An average of almost 5 million Btus is used per tonne of clinker. In 2004, the cement sector consumed 422 trillion Btus of energy, almost 2% of total energy consumption by US manufacturing (PCA, 2003).

Coal is the primary energy source for cement production, followed by petroleum coke and purchased electricity, a high percentage of which is produced from coal. Low-cost waste fuels are also used, including burning waste oil and scrap tires, solvents, unrecyclable plastics, and other waste materials.

13.2.2.3 Solid wastes

The major waste material from cement manufacturing is cement kiln dust (CKD). An industry average of 38.6 kg of CKD is generated per tonne of cement. Approximately 79% of this is landfilled and 21% is recycled (Medgar, Nisbet, & Van Geem, 2006).

13.2.2.4 Water use and discharge in cement production

Water is used in cement production to suppress dust, to condition or cool kiln exhaust gases, to finish mills, and for noncontact cooling. About 1 tonne of water is discharged in the production of 1 tonne of cement. Effluents result from quarry dewatering, storm water runoff of facilities, CKD pile runoff, and landfill wells. Discharged water contains suspended solids, aluminum, phenolics, oil and grease, nitrates, dissolved organic compounds, chlorides, sulfates, ammonia, zinc, and pH (Medgar et al., 2006).

13.2.2.5 Energy benefits by using slag in cement manufacture

Around 1990, the average energy consumption in the United States for the production of 1 tonne of cement by the dry process was 1.6 MWh. In modern plants, this figure is much reduced, being below 0.8 MWh in Austria. 1.96 electricity consumption, which accounts for some 6–8% of total energy used, is typically of the order of 10 kWh for crushing the raw materials, 28 kWh in the raw meal preparation, 24 kWh in burning, and 41 kWh in grinding (Neville, 1996).

It is not difficult to compare the energy consumption between blended cement incorporating steel slag and granulated blast furnace slag (GBFS). If 20% or so steel slag can be used, with no strength loss, in steel slag blended cement (SSBC) manufacture, the benefits of reduced energy consumption can be calculated. The energy consumed in ordinary Portland cement (OPC) clinker manufacture (calcining) was approximately 6.1 GJ/tonne-clinker for a wet process cement plant in the 1990s. In addition, the electricity consumed for grinding is of the order of 100 kWh/tonne with up to 1000 kWh/tonne for superfine grinding (below 120 μm) (Lowrison, 1974; Wang, 1992). The comparison of energy consumed is as follows:

For clinker:

Grinding of raw materials—100 kWh/tonne-raw materials 100 × 3.6 MJ = 0.36 GJ/tonne;
Calcining of clinker—6.1 GJ/tonne-clinker;
Grinding of clinker—100 kWh/tonne-clinker 100 × 3.6 MJ = 0.36 GJ/tonne;
The total energy consumed is 6.82 GJ/tonne.
The energy consumption reduced to 4.80 MJ/tonne (Medgar et al., 2006).

For steel slag:

Grinding of steel slag—100 kWh/tonne-slag = 0.36 GJ/tonne.

Therefore, the energy consumed in processing steel slag is about 5.3% of that in processing OPC clinker. Energy, of course, is consumed during the manufacture of steel and the production of the steel slag; however, this is a separate process. The comparisons stated above are based on the assumption that the slag is readily available as an existing material.

Table 13.2 gives a typical example of a quantitative evaluation of the contribution of iron blast furnace (BF) products to CO_2 reduction and energy saving by using slag in cement production (Nakagawa, 2007).

Table 13.2 **CO_2 reduction due to using slag cement**

		1—OPC	**2—BF slag cement**	**CO_2 reduction**	
				kg: 1 − 2	***%***
Limestone (kg)		453	278	−278	39
Energy	Fuel (kg)	293	192	−103	−34
	Power (kWh)	11	9		
Total CO_2 emission (kg)		757	479	−278	37

Data from Nakagawa, M. (2007). The current state of the use of iron and steel slag products in Japan. *In Proceedings of the 5th European slag conference, September 19–21, Luxembourg*.

Except when the raw materials necessitate the use of the wet process, the dry process is used nowadays to minimize the energy required for burning. Typically, the burning process represents 40–60% of the production cost, while the extraction of raw materials for the manufacture of cement represents only 10% of the total cost of cement.

13.3 Cementitious properties of slags and their utilization in cement manufacture

GBFS has been used in cement manufacture for several decades. Steel slag has also been investigated to make SSBC or use as a raw material. GBFS cement has several good properties that improve concrete. Research on SSBC has also revealed benefits and presented promising results. Recently, copper slag and municipal incinerator slag have also been used in the laboratory for cement research.

13.3.1 Hydraulic activity of GBFS

BFS is cooled very rapidly and solidifies as a glass. The granulated slag is poured into a large excess of water (100 m^3/tonne of slag) or subjected to spraying jets under 0.6 MPa pressure (water, 3 m^3/tonne of slag). After the treatment, the water content of slag (≤30%) is eliminated in dryer mills or filter basins (Hewlett, 1998). Fig. 13.2 shows the granulation process of BFS.

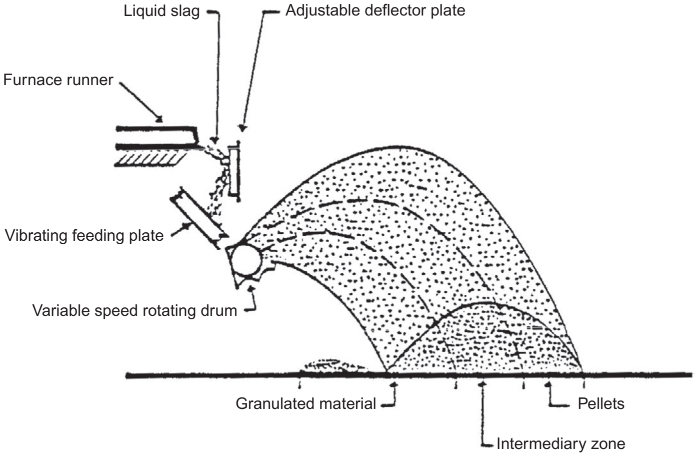

Fig. 13.2 Granulation of BFS.

GBFS was first developed in Germany in 1853. Ground slag has been used as a cementitious material in concrete since the beginning of the 1900s. Ground GBFS, when used in general purpose concrete in North America, commonly constitutes between 30% and 45% of the cementing material in the mix. Some slag concretes have a slag component of 70% or more of the cementitious material. ASTM C989 (AASHTO M302) classifies slag by its increasing level of reactivity as Grade 80, 100, or 120 (Table 3.1). ASTM C1073 covers a rapid determination of hydraulic activity of ground GBFS and ACI 233 (1995) provides an extensive review of slag.

Regarding activation, the best-known activator is OPC. Fifteen experimental studies have shown that the main hydration product of pure BFS is an amorphous gel CSH (Ca–Si–H_2O or calcium silicate hydrate), which is the same as that of pure OPC. The main hydration product CSH of pure BFS has a much lower C/S ratio (approximately 1.1) than that obtained from the OPC (approximately 1.8). The hydration of BFS in the blended cement exhibits the same product CSH, while the C/S ratio in the CSH is highly dependent on the chemical compositions of both reactants, viz. OPC and BFS, and also the BFS proportions in the OPC. The steelmaking slags are referred to by the steel production techniques used, such as basic oxygen furnace (BOF), electric arc furnace (EAF), ladle furnace, and so forth, in the basic oxygen steelmaking process (Alanyali, Col, Yilmaz, & Karagoz, 2009).

Ground GBFS (Fig. 13.3) is made from iron BFS; it is a nonmetallic hydraulic cement consisting essentially of silicates and aluminosilicates of calcium developed in a molten condition simultaneously with iron in a BF. The molten slag at a temperature of about 1500°C (2730°F) is rapidly chilled by quenching in water to form a glassy sand-like granulated material. The granulated material, which is ground to less than

45 µm, has a surface area fineness of about 400–600 m^2/kg Blaine. The relative density (specific gravity) for ground GBFS is in the range of 2.85–2.95. The bulk density varies from 1050 to 1375 kg/m^3 (66 to 86 lb/ft^3). The rough and angular-shaped ground slag (Fig. 13.4) in the presence of water and an activator, NaOH or CaOH, both supplied by OPC, hydrates and sets in a manner similar to PC.

Fig. 13.3 Ground GBFS.

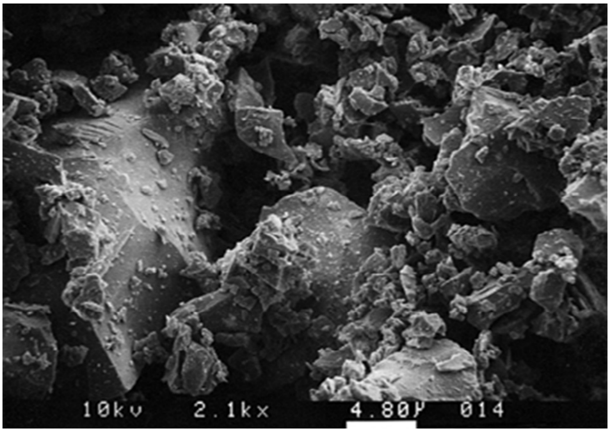

Fig. 13.4 Scanning electron microscope micrograph of slag particles at 2100×.

13.3.1.1 *Hydraulic activity*

There is general agreement among researchers, that the principal hydration product that is formed when ground GGBFS is mixed with PC and water is essentially the same as the principal product formed when PC hydrates; that is, CSH. As seen in the ternary diagram in Fig. 13.5, OPC and GGBFS lie in the same general field, although OPC is essentially in the tricalcium silicate (C_3S) field whereas GGBFS is found essentially in the dicalcium silicate (C_2S) field of the diagram. GGBFS hydrates are generally found to be more gellike than the products of hydration of OPC, and so add denseness to the cement paste. When GGBFS is mixed with water, initial hydration is much slower than OPC mixed with water; therefore, OPC or alkali salts or lime are used to increase the reaction rate. Hydration of GGBFS in the presence of OPC depends largely upon breakdown and dissolution of the glassy slag structure by hydroxyl ions released during the hydration of the OPC. In the hydration of GGBFS, the GGBFS reacts with alkali and calcium hydroxide ($Ca(OH)_2$) to produce additional CSH. Research found that a very small immediate reaction also takes place when GGBFS is mixed with water, preferentially releasing calcium and aluminum ions to solution. The reaction is limited, however, until additional alkali, calcium hydroxide, or sulfates are available for reaction. Research in the 1970s suggested that, in general, hydration of ground GGBFS in combination with OPC at normal temperature is a two-stage reaction. Initially and during the early hydration, the predominant reaction is with alkali hydroxide, but subsequent reaction is predominantly with calcium hydroxide. Calorimetric studies of the rate of heat liberation show this two-stage effect, in which the major amount of GGBFS hydration slags behind that of the OPC component.

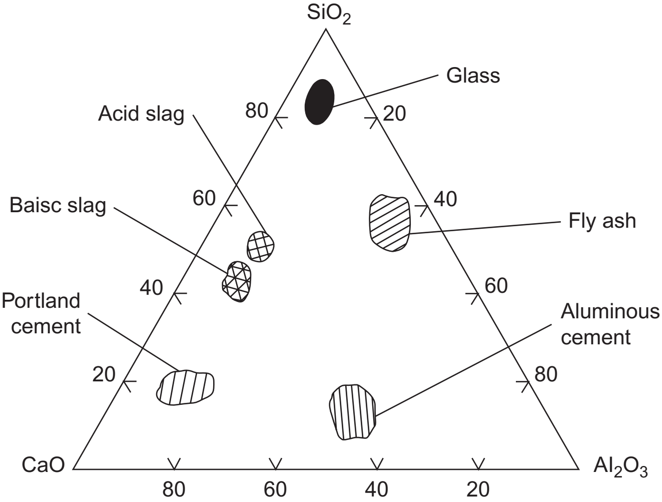

Fig. 13.5 Tertiary diagram of slags and Portland cement.

With increasing temperature, the alkali hydroxides from the cement have greater solubility; therefore, they predominate in promoting the early reactions of the GGBFS.

GGBFS is thus able to chemically bind a larger amount of alkali in the CSH because of the calcium to silica ratio of the CSH formed from GGBFS is lower than that formed from PC. Research has shown that alkali hydroxide alone (ie, without calcium hydroxide from PC hydration) can hydrate GGBFS to form a strong cement paste structure that may be used in special application.

13.3.1.2 Factors determining cementitious properties

The clarification of the basic principles of slag hydration makes it possible to identify the primary factors that in practice will influence the effectiveness of the uses of GGBFS in hydraulic cement. These factors are (i) chemical composition of the GGBFS; (ii) alkali concentration of the reacting system; (iii) glass content of the GGBFS; (iv) fineness of the GGBFS and PC; and (v) temperature during the early phases of the hydration process.

Due to the complexity of the influencing factors, it is not surprising that earlier attempts to relate the hydration of GGBFS to simplified chemical moduli failed to provide adequate evaluation criteria for practice. The complexity of the reacting system suggests that direct performance evaluations of workability, strength characteristics, and durability are the most satisfactory measures of the effectiveness of GGBFS use. The ASTM C989 slag activity index is often used as a basic criterion for evaluating the relative cementitious potential of a GGBFS. Furthermore, proportioning for particular performance requirements should be based on tests of concrete including GGBFS.

13.3.2 GBFS in cement manufacture

GBFS has long been used in cement manufacture to make slag cement. There are a number of standards globally describing the conditions of how granulated BFS is used to produce commercialized blended cements. The ground GBFS, or GGBFS was also used directly in concreting several decades ago. GGBFS is used to exploit its specific properties: lower early strength and better final strength, slightly lower water demand, refinement of the pore structure of the concrete, lower permeability, lower heat of hydration, and better resistance against sulfate attack and alkali reaction. Different factors can influence the quality of the GGBFS used regarding the chemistry, granulation, internal logistics, outside logistics, grinding, and activation (Alanyali et al., 2009). The content of GGBFS can be as high as 60–80%. Most BFS is used in cement production and the share of the BFS has been increasing. For example, in Japan, in the 1960s, BF cement shared the domestic cement market at approximately 5%, or 2.5 million tonnes per year. After the second oil crisis in 1979, GBFS use in cement increased rapidly due to the natural resources and energy saving of slag use. As the consequence of the efforts of the industry and government, including the inclusion of GBFS into national standards and installation of more GBFS grinding mills, the BFS cement increased to 16.13 million tonnes, accounting for 24.5% of the Japanese cement market in 2005. In the meantime, Japan also exported 6.7 million tonnes of GBFS in 2006, accounting for more than 40% of its shipments of cement (Nakagawa, 2007).

13.3.2.1 Use directly in concrete

GGBFS also is used directly as mineral addition to concrete because of better financial benefits, as the sale price for ground slag is approximately 80% of that of the OPC price (Alanyali et al., 2009).

13.3.2.2 Slag cement use for special applications

Slag cements disappeared from the market mainly because they presented relatively low mechanical resistance at first aging and failed to present other competitive advantages concerning cement other than lowering the price. These limitations have now been overcome by significant advances in scientific knowledge on building materials (Coelho, 2004). Some researchers show it to be possible to formulate slag cements, which, contrary to common cement, may be reinforced with natural fibers. At present, some prefabricated concrete and glass fiber-reinforced cement manufacturers have been showing interest in technology transfer research and actions related to activating BFS. Many other alternatives for specific applications of slag cements can be developed through scientific research allied to an adequate market opening strategy.

13.3.3 Mineral compositions and hydraulic activity of steel slag

In general practice, steel slag is not subjected to a granulation process that is rapid cooling. Therefore, they have crystalline structures of various crystalline phases as a result of natural air-cooling. Not many of the specific properties of GGBFS explained earlier can be attributed to steelmaking slags, except for lower heat of hydration and better resistance against sulfate attack and alkali reaction. Furthermore, BOF slag chemistry is also considerably comparable, but the EAF slag chemistry may be variable from plant to plant.

13.3.3.1 Basicity of alkalinity of steel slag

The basicity of alkalinity ($A = CaO/SiO_2 + P_2O_5$) has been adopted as a basis for classifying the steel slags. According to this basicity ratio, there could be four types of steel slags:

(i) Olivine group ($A = 0.9$–1.4);
(ii) Merwinite group ($A = 1.4$–1.6);
(iii) Dicalcium silicate group ($A = 1.6$–2.4)
(iv) Tricalcium silicate group ($A > 2.4$)

It appears logical that high basicity ratios would favor the hydraulic activity of a given steel slag (Chatterjee, 2001).

13.3.3.2 Calculation of active mineral in steel slag

To date, all calculations of the active composition in steel slag have been based on its chemical composition in terms of the Bogue formula (Lea, 1970). Although such calculation is approximate, because of the complexities of the state of solid solution and small quantity (ranging from 1% to 6%) of CaO existing in the free state in steel slag, the components of steel slag can generally be estimated and explained.

The Bogue formula can be expressed as:

$$C_3S = 4.07C - 7.60S - 4.47A - 2.86F - 2.86\overline{S};$$

$$C_2S = 8.60S + 3.38A + 2.15F + 2.15\overline{S} - 3.07C, \text{or} = 2.87S - 0.754C_3S;$$

$$C_4AF = 4.77A;$$

$$C_2F = 1.70\left(F - 1.57A\right);$$

$$C\overline{S} = 1.70\,\overline{S}$$

13.3.3.3 Existing form of free CaO and its effect on stability

It has been proven from different approaches that the effect of free CaO on the stability of steel slag itself not only depends on the amount, but also on the form and grain size of the free CaO.

Analysis has shown that there exists two types of free lime in steel slags, the pure one and the solid solution. The former is free CaO and the latter CaO + x% FeO ($0 < x < 10\%$ by weight). They can be distinguished in XRD patterns, free CaO having $d = 2.41$, and free CaO in solid solution state having $d = 2.38$. Excessive free lime, especially in the presence of solid solution with small amounts of FeO, is the primary cause of volumetric unsoundness of SSBC (Wang & Xie, 1980).

It has been reported by Geiseler and Schlosser (1988) that, from microscopic investigation, it is evident that the free lime can exist in the form of residual lime and lime precipitated during solidification and subsequent cooling. In both categories, forms exist that are different in appearance and particle size. The residual lime can be classified into grainy lime with particle size mainly between 3 and 10 μm and spongy lime with particle size mainly between 6 and 50 μm. The precipitated lime can exist on C_2F grain boundaries or within C_3S crystals and has particle size usually less than 4 μm. All types of free lime can hydrate; however, the most significant is the so-called spongy free lime with grain size up to 50 μm and that is a form of residual lime (refer to Fig. 2.6 in Chapter 2).

Conflicting proposals have been put forward for limiting the content of free CaO, and it would appear that the permissible content is dependent on the end use of the materials. For example, it has been reported that the use of steel slag in an experimental road has shown that slag with contents of free lime less than 7% causes no damage (Geiseler & Schlosser, 1988) and that a high free lime content of the steel slag (11.6%) does not cause unsoundness of blended mortars (Duda, 1989). With regard to the stability of steel slag itself, a content of 4–5% free CaO has been considered by many researchers to be the upper limit for stability (Conjeaud, George, & Sorrentino, 1981). From this it is suggested that, when assessing the stability of the steel slag, it is important to consider the condition for use of steel slag and the properties of the matrices in which steel slag exists when it is a component material in a composite. Varying free CaO contents may be acceptable, depending on end use of the material and degree of constraint placed on the matrix. A criterion for steel slag use in blended cement in terms of free lime is presented in Section 13.4.3.

13.3.3.4 Effect of MgO on the stability of SSBC

Microscopic studies have shown that, in steel slag, magnesium oxide exists mainly in solid solution with FeO and MnO, so-called magnesia wüstites, while unbound MgO (periciase) is seldom found. The unbound MgO also includes the macroscopically visible fragments of undissolved refractory lining or dolomite that were found in some slags.

Luo (1980) proposed that the percentage ratio by weight of MgO to FeO plus MnO determines whether the MgO is stable or not, where

$$\frac{\mathrm{MgO}}{\mathrm{FeO}+\mathrm{MnO}}<1,\quad \text{MgO is stable}$$

$$\frac{\mathrm{MgO}}{\mathrm{FeO}+\mathrm{MnO}}>1,\quad \text{MgO is unstable}$$

Iron mainly exists as bivalent iron (FeO), which accounts for 70% of the total iron content in steel slag (apart from electric arc slag). The ratio is less than 1 for most steel slags. The equation is based on the premise that MgO can form solid solution with FeO and MnO.

Investigations concerning the free magnesia content of steel slags have shown that good dissolution of the added dolomite in the furnace is most important. For this purpose the dolomite should be added at an early stage of the steelmaking process and grain size should be as small as possible to enable the dolomite to dissolve and react completely.

Four significant phases can be clearly observed: calcium silicates, dicalcium ferrite, and a solid solution of magnesium iron oxide in XRD patterns and alumino ferrite calcium phases can be found in microprobe analysis (Mahieux, Aubert, & Escadeillas, 2007), and no magnesium oxide is visible in XRD patterns. All the magnesium oxides were combined with iron oxides to form a solid solution of magnesium iron oxide.

However, the use of steelmaking slags as a cementing component should be given a priority in terms of technical, economical, and environmental considerations. There is no global standard available that specifies the usage of steelmaking slags in cement production, except for the GB/T 12957-05 Chinese National Standard, which specifies the method for the testing of steelmaking slags' hydraulic reactivity in determining the steelmaking slag to be used as a cement mixture additive. Furthermore, the GB 13590-92 Chinese National Standard specifies the composition, properties, testing, storage, and applications for steel and iron slag cement. A specialty Portland clinker—Steelmaking Slag—Blast Furnace Slag Cement (PSSBFC), which is composed of approximately 30% steelmaking slag, 30% ground granulated BF iron slag, 35% Portland clinker, and 5% gypsum, has been commercially marketed in China for more than 20 years. According to the GB 13590-92 Chinese National Standard, the total amount of steelmaking slag and ground granulated BF iron slag should not be <60% by weight. This type of cement has the disadvantages of a longer setting time and lower early strength, but the advantages of a lower energy cost, higher abrasion resistance, lower hydration heat evolution, higher later strength development, and better sulfate resistance compared with PC. PSSBFC can be used for general construction uses, and is especially suitable for mass concrete and pavement applications due to its special features. The production of PSSBFC consumed approximately 40% of the total steelmaking slag production of China in the 1980s. The main mineral phases of BOF steelmaking slags are dicalciumsilicate, dicalciumferrite, and wüstite (Alanyali et al., 2009).

13.3.4 The use of steel slag in cement manufacture

13.3.4.1 The process

There are two ways of incorporating steel slag in cement manufacture. One involves the use of the slag as a raw material for cement clinker; that is, steel slag is calcined in the kiln together with other raw materials. In calcining, steel slag is treated as one of the raw materials to be calcined with other raw materials, such as clay and limestone. This can be regarded as a partial substitution of limestone (Kondo, Daimon, Asakawa, & Ito, 1974).

Sersale, Amicarelli, Frigione, and Ubbriaco (1986) used steel slag as one of the raw materials of cement clinker. It demonstrated that a substitution of 10% steel slag appeared to be effectual, without detriment to the properties of the resultant cements and energy savings during the clinkering process were received.

The other way of incorporating steel slag in cement manufacture is a noncalcining process, intergrinding steel slag with GBFS and OPC clinker to make blended cement. There are three methods in the noncalcining process: (i) nonclinker (no OPC clinker blended), steel slag ground with GBF slag and gypsum; (ii) low clinker (low quantities of OPC clinker blended, usually less than 50% by weight), steel slag ground separately, then the addition of ground OPC clinker as a blend; and (iii) low clinker, steel slag interground with OPC clinker (Fig 13.6).

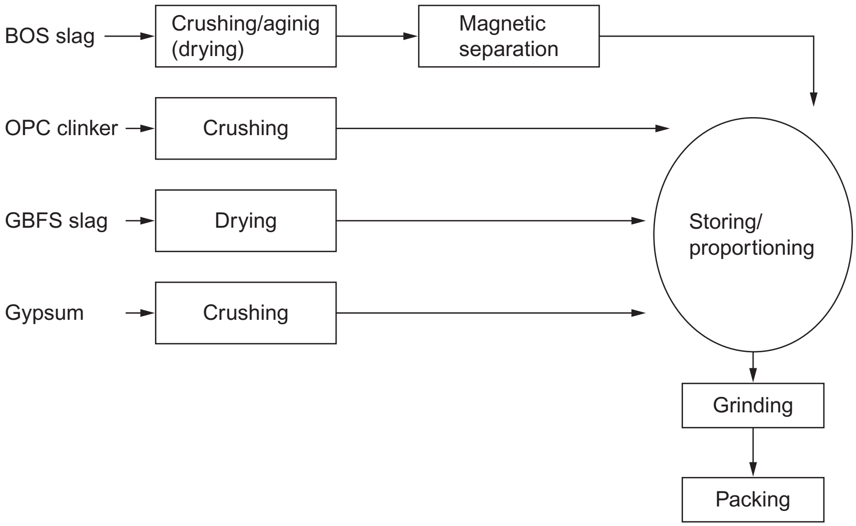

Fig. 13.6 Blended steel slag cement manufacture process.

Due to the potential for energy saving, the noncalcining process is generally preferred. Normally, steel slag, GBF slag, OPC clinker, and gypsum are mixed and ground together. An activator may be added to stimulate slag activity. The activators used may be NaOH, $CaCl_2$, $Ca(OH)_2$, $CaSO_4 \cdot 2H_2O$, and KF. The materials are generally ground to Blaine fineness greater than 3500 cm^2/g.

13.3.4.2 Mixing proportion and strength

Four basic materials—steel slag, GBF slag, OPC clinker, and gypsum—are the component materials of SSBC. In some cases, only steel slag and gypsum were used, but this is generally only for comparison of hydraulic activity purposes and is not for practical use. Additions of steel slag are usually in the range from 10% to 55% by weight of the total component materials, with GBF slag, OPC clinker, and gypsum constituting the remainder. The addition of GBF slag may increase the strength of the SSBC; however, excessive amounts (above 55% by weight) may decrease the strength and influence the durability at late age. Overdosing with gypsum may decrease late age strength. In general, a gypsum content of 8% by weight of total solid materials is considered as optimum.

The strength of SSBC may be similar to that of OPC when the incorporated amount of steel slag is lower than 35% and the content of OPC clinker is greater than 55% by weight of constituent materials. If the content of OPC clinker is lower than 55%, the strength of SSBC decreases by 5% for each 10% reduction in the amount of OPC clinker.

Compressive strength of 49.3 MPa at 28 days was reported by Wang and Lin (1983) for paste specimens containing 35% steel slag, 60% OPC clinker, and 5% gypsum, and 66.5 MPa was obtained for specimens containing 18% steel slag, 60% OPC clinker, 18% GBF slag, and 4% gypsum.

Idemitsu, Takayama, and Watanabe (1981) reported compressive strength of 49.2 MPa for SSBC specimens containing 60% steel slag, 33% GBF slag, 4% gypsum, and 3% calcium chloride as an activator.

Sun and Yuan (1983) made specimens with steel slag and gypsum only. The early strength of this SSBC was generally rather low. The 7-days compressive strength was about 40% of that at 28 days; but at later ages, the strength increased more rapidly, with the 90-days compressive strength reaching 125–140% of 28 days compressive strength. The stability of the specimens was not acceptable after steam treating.

Laboratory research results have shown that the compressive strength of mortar made with SSBC containing 45% basic oxygen steel (BOS) slag, 45% GBF slag, and 10% gypsum by weight is related to the C_3S content of the steel slag used (Sun & Yuan, 1983). When C_3S content is less than 20%, the compressive strength at 28 days will be less than 10 MPa; for levels of C_3S above 20% by weight, the effect of C_3S content on the compressive strength increases appreciably; when C_3S is more than 40%, without exception, all 28 days compressive strength results exceed 30 MPa. The 28-day compressive strength of the SSBC can attain values similar to those of OPC, provided that not more than 35% slag content is added.

The SSBC containing GBFS has proven to be more successful, with regard to strength and sulfate resistance, than steel slag–cement clinker blends. This is due to a reduction in $Ca(OH)_2$ content, caused by C_3S and C_2S hydration in GBF–steel slag–OPC clinker blends, compared with that of the steel slag–OPC clinker blends and the combination of $Ca(OH)_2$ with the active component of GBF slag. The greatly decreased $Ca(OH)_2$ content and the Increased production of low alkali CSH gel and ettringite result in a more dense hydrated structure.

13.3.4.3 Laboratory pilot experimental study using BOF slag in blended cement–materials for strength and stability testing

To explore the feasibility of using BOF slag for SSBC manufacture, preliminary experiments on the hydraulic properties and stability of SSBC were performed utilizing five materials: BOF slag 1, which was freshly produced; BOF slag 2, which had been exposed to air for 1 year; GBF slag; OPC clinker; and gypsum. The two steel slag samples have a particle size less than 12 mm.

The BOF slag and GBF slag were dried to constant weight and both of the steel slag samples were magnetically separated before grinding. Approximately 20–22% magnetics were separated from each slag sample, being particles incorporating iron scrap. The materials were individually ground in a laboratory ball mill. The Blaine fineness of the steel slag after grinding was around 2640 cm²/g. Sieve analysis indicated the weight retained on a 75 μm sieve to be 27% for OPC, 34% for BOF slag 1, and 31% for BOF slag 2. The chemical composition of steel slag used has the range shown in Tables 13.3 and 13.4, respectively.

Table 13.3 **Typical range of chemical composition (% by weight) of steel slag used**

Constituent	Content (%)	Constituent	Content (%)
Total Fe (as FeO)	25.2–28.1	K_2O	0.02–0.03
SiO_2	12.7–13.2	TiO_2	0.95–0.97
Al_2O_3	3.0	Na_2O	0.12–0.14
CaO	36.7–39.3	S	0.08–0.09
MnO	4.0–4.1	P	0.68–0.74
MgO	8.8–9.2	Cr_2O_3	0.17–0.30
		Total	95.4–96.2

Table 13.4 **Typical range of chemical composition (% by weight) of GBF slag used**

Constituent	Content (%)	Constituent	Content (%)
FeO	0.78–1.58	K_2O	0.34–0.44
SiO_2	33.84–35.56	Na_2O	0.19–0.37
Al_2O_3	13.87–14.53	S	0.44–0.58
CaO	40.31–41.69	P	0.005–0.009
MnO	0.34–0.44	TiO_2	0.55–0.59
MgO	6.42–6.78		

13.3.4.4 Experimental method and strength results

The individually ground materials and tap water were combined to form four separate mixes as specified in Table 13.4. The solid materials were dry mixed in a rotary mixer for 10 s prior to the addition of the mixing water, with a total mixing time of 5 min. Twenty-eight cement paste cube specimens of 25 mm dimension were made from each mix for unconfined compressive strength and autoclave testing. Specimens from mixes No. 1 and No. 2 were demolded 3 days after molding, as their strength was insufficient to permit demolding at earlier ages. Specimens from mixes No. 3 and No. 4 could be demolded after 24 h as the addition of 10% OPC clinker resulted in higher early strength. The specimens were cured in water at 23 ± 2°C until tested. The compressive strength results are shown in Table 13.5, each result being an average for three specimens.

The compressive strength results for the slag pastes are lower than those generally exhibited by conventional OPC pastes. This is considered to be largely because the finenesses achieved for the raw materials in the laboratory ball mill are substantially lower than that of commercially produced OPC. Calculations based on chemical analysis for samples of BOF slag 1 and BOF slag 2 shows the basicity to be 2.82 and 2.74, the C_3S content 24.37% and 15.07%, and the C_2S content 19.51% and 25.0%, respectively. The slags are consistent with high activity (basicity) slag.

Research on BOF slag under XRD examination has shown that the main minerals present in BOF slag are calcium silicates (Ca_2SiO_4 and Ca_3SiO_5), dicalcium ferrite ($Ca_2Fe_2O_5$), calcite ($CaCO_3$), Portlandite ($Ca(OH)_2$), lime (CaO), and a solid solution of magnesium iron oxide (MgO_xFeO_y). The reactivity of BOF slag was studied using XRD on hydrated slag pastes. BOF slag is poorly reactive with water: the hydration of free lime leads to the formation of Portlandite and a few parts of tricalcium silicate forms calcium silicate hydrated. In spite of these reactions, no setting and no hardening were observed on hydrated material. The free lime contained in the BOF slag could activate GGBFS to produce SSBC.

Mahieux et al. (2007) used BOF slag with a constant amount of catalyst (5%) to make SSBC with a constant BOF slag/GGBFS ratio of 0.8. The maximum value of the compressive strength is reached for the mixture containing 42.5% of BOF slag. GGBFS is much more reactive than BOF and so the compressive strength increases with the amount of GGBFS contained in the mixtures. In parallel, GGBFS needs the free lime contained in BOF to react. The amount of free lime has to be sufficient to activate the GGBFS and this explains the decrease of compressive strength for the mixtures containing low proportions of BOF slag.

13.3.4.5 BOF slag used in cement clinker making

BOF slag produced from the Kardemir Steelworks was used as a raw material for cement clinker making as reported by Alanyali et al. (2009). The study confirmed that the compressive strength of cement with up to 30% BOF slag was within the values of 325 and 425 steelmaking slag cement.

13.3.5 Hydraulic activity of nonferrous slags and utilization

13.3.5.1 Hydraulic properties of granulated copper slag

Copper slag granulated by water quenching produces vitreous amorphous solid particles that show higher chemical stability than those air-cooled solidified (Pavéz, Rojas, Palacios, & Nazer, 2004).

Table 13.5 Mix proportions and compressive strength development of SSBC pastes

Mix proportion (% by weight)					Water (as % of solid)	Unconfined compressive strength (MPa)			
	BOF slag	GBF slag	OPC clinker	Gypsum		28 days	60 days	90 days	225 days
1. BOF slag 1	45	45	0	10	21.0	22.5	24.9	31.2	–
2. BOF slag 2	45	45	0	10	21.4	31.0	34.3	36.4	–
3. BOF slag 1	40.5	40.5	10	9	22.0	34.5	38.7	35.7	61.8
4. BOF slag 2	40.5	40.5	10	9	22.0	26.5	35.9	38.7	67.3

The chemical composition of copper slag varies with the type of furnace. The typical composition of smelting slags is Fe (as FeO, Fe_3O_4) 30–40%; SiO_2 35–40%; Al_2O_3 up to 10%; and CaO up to 10%.

The density of copper slag varies between 3.16 and 3.87 g/cm^3 based on the amount of iron content. The average specific gravity of copper slag is about 3.5 g/cm^3, which means copper slag is denser than ordinary natural aggregates. In general, water absorption of copper slag is very low. As stated previously, when liquid slag is cooled slowly, it forms a dense, hard crystalline product whereas quick solidification by pouring molten slag into water gives granulated amorphous slag. Granulated copper slag has higher water absorption and less unit weight compared with air-cooled copper slag due to its more porous texture.

The molten slag is discharged from the furnace at 1000–1300°C. If the molten slag is water quenched, a glassy copper slag is obtained. Because copper slag usually has a low content of CaO, granulated copper slag exhibits pozzolanic properties. As CaO content in copper slag increases, it can exhibit cementitious properties. A study indicated that a copper slag that contains approximately 19% CaO shows a good cementitious property under the activation of NaOH. The strength of NaOH-activated copper slag mortars even exhibit a higher strength than PC mortars after 4 h of curing at 80°C. These NaOH-activated copper slag and PC mortars are immersed in water and in a corrosive solution that contains 230 g/L NaCl, 64 g/L $MgCl_2$, 15 g/L KCl, and 14 g/L $MgSO_4$. The strength of the NaOH-activated copper slag mortars slightly increases with time regardless of being immersed in water or in the corrosive solution. Study also shows that NaOH-activated coper slag mortars have better corrosion resistance than PC mortars (Shi, Meyer, & Behnood, 2008; Shi & Qian, 2000; Murari, Siddique, & Jain, 2015).

13.3.5.2 Granulated copper slag use in blended cement

By using copper slag as a partial replacement of cement, substantial amounts of energy required for production of cement will be saved because its use needs only grinding. The reports of the Portland Cement Association show that copper slag has been used in full-scale cement manufacturing in different plants.

Mobasher, Devaguptapu, and Arino (1996) used 15% copper slag to replace PC. Activation of poszzolanic reactions were studied using up to 1.5% hydrated lime. Hydration reactions were monitored using quantitative X-ray diffraction and the porosity was examined using mercury intrusion porosimetry (MIP). Results indicate a significant increase in the compressive strength for up to 90 days of hydration. Decreases in capillary porosity measured using MIP indicated densification of the microstructure. The embrittlement due to the addition of slag is measured using parameters. Fracture properties such as critical stress intensity factor, and fracture toughness, G_f, showed a constant or decreasing trend with the addition of slag.

13.3.5.3 Use of copper slag in cement clinker production

Copper slag has a high Fe content and has been used as an iron adjustment material during the cement clinker production. Because the main composition of copper slag is vitreous $FeSiO_3$, it has a low melting point and could reduce the calcination temperature for cement clinker. Thus, the use of copper slag to replace iron powder as iron-adjusting materials facilitates cement production, reduces or eliminates the need of mineralizer. However, the use of iron powder does not show this advantage.

The performance testing results indicated that cement produced by using copper slag performed even better than using iron powder. In another publication, it was reported that copper slag was successfully used as an iron-adjustment material in cement clinker production. Used in the plant, limestone (55–60%), marl (35–40%), and copper slag (2.5–6%) are used as cement raw materials for the production of clinker. The clinker is then finely ground in a ball mill grinding circuit together with a small amount (typically 4%) of gypsum to produce cement in the Turkey Trabzon Cement Plant (Alp, Deveci, & Süngün, 2008).

The use of copper slag also results in lower required calcination temperature and improved grindability of the clinker, although the raw materials cost may or may not be reduced depending on the local availability of copper slag.

13.3.5.4 Use of copper slag in blended cement

The use of copper slag as a pozzolanic material for a partial substitute for ordinary PC and its effects on the hydration reactions and properties of mortar and concrete have been reported in several publications (Al-Jabri, Taha, Al-Hashmi, & Al-Harthy, 2006; Ariño & Mobasher, 1999; Deja & Malolepszy, 1989; Douglas & Mainwaring, 1986). Roper, Kam, and Auld (1983) reported that copper slag does not need to be completely glassy for significant hydration to occur. One potential concern for such materials is their heavy metal content and the leaching characteristics. The leachability of copper, nickel, lead, and zinc ions from copper slag was lower than the regulatory limits.

In terms of the leachability limits, Zain, Islam, Radin, and Yap (2004) reported that the mortar incorporating waste copper slag up to 10% replacement is safe with respect to leachability of the above heavy metal based on the mentioned standards. Sanchez de Rojas, Rivera, Frias, Esteban, and Olaya (2004) showed that the copper slag incorporation into the cement mortar does not cause an increase in the leached elements.

13.3.5.5 Municipal solid waste incinerator bottom ash slag

Incineration is expected to become a major municipal waste management alternative, as it is not only effective in terms of waste volume reduction, but can also produce benefits in terms of energy recovery. A large amount of incinerator ash slag is generated. The major components in bottom ash slag are SiO_2, CaO, and Al_2O_3. The SiO_2 content increases as the particle size of the bottom ash increases, but the CaO increases as the particle size of bottom ash decreases. Heavy metals are mainly found in the finer fraction (Lin & Lin, 2006).

About 50% or more of treated municipal solid waste incinerator (MSWI) bottom ash is used as secondary building material or for similar purposes, such as for roadbeds, the construction of embankments, and other civil engineering applications. Nevertheless, bottom ash is subject to chemical problems, which can induce expansion, which in turn brings about cracking, and finally road destruction.

Lin et al. used municipal incinerator ash slag cement in a study (Lin & Lin, 2006; Lin, 2005; Lin, Chang, & Lin, 2008). Thermal treatment tests were performed with water-quenched bottom ash taken from a MSWI. The ash was screened and magnetically separated to remove any coarse nonferrous impurities and ferrous substances, then dried at 105°C for 24 h. The cement used in this research was Type I OPC.

The MSWI bottom ash slag was prepared by melting the above bottom ash in a 20 L capacity electric-heated melter at 1400°C for 30 min. The melts were water quenched to obtain fine slag, which was then ground in a ball mill until fine enough to pass through a no. 200 sieve. The resultant pulverized slag had a specific surface of approximately 500 m^2/kg, with a specific gravity ranging from 2.7 to 2.9, close to that of OPC.

SSBC pastes were mixed homogeneously with cement, slag made from MSWI bottom ash, and water, in a mixer. The substitution levels of slag in the blended cement were between 10% and 40%. The water-to-binder ratio of SSBC paste was constant, 0.38. After curing for 1, 3, 7, 14, 28, 60, or 90 days, the SSBC paste cubes were subjected to unconfined compressive strength tests.

The Toxicity Characteristic Leachate Procedure leaching concentrations of the target metals in the MSWI bottom ash slag all met the Taiwan EPA's current regulatory thresholds, indicating that the heavy metals had been immobilized in the vitrified product, making then highly resistant to leaching.

In terms of strength development, in the first 7 days, the use of the slag lowered the strength of the paste. The results also indicate that the cementitious reactions of the slag tended to retard the cementitious reactions during the early stages. This may be due to reactions in the slag, which consumed part of the calcium hydroxide formed during the earlier stages of hydration. However, at a later stage (28–90 days), the compressive strength of SSBC paste samples containing 10% and 20% substitution levels of slag varied from 95% to 100% of that developed by the plain PC paste. The compressive strength development by the 40% substitution levels of slag, at 7, 28, and 90 days, exhibited a decline in the compressive strength of 58%, 81%, and 90%, respectively, compared to that developed by the plain cement paste.

13.4 Special considerations for slag use in cement manufacture

As has been known, the major concerns with the use of BOS slag in SSBC manufacture have been associated with two issues. One is whether the BOS slag has sufficient volume stability during its service period. If the stability of SSBC is not acceptable, it will lose service significance. The second issue concerns the grindability of BOS slag used in SSBC manufacture. As is known, the main energy consumed during cement manufacture is in the process of calcining and grinding. If the energy consumed in steel slag grinding/magnetic separating is more than that for calcining and grinding of raw materials and clinker, BOS slag will lose its economic significance as an additive of blended cement. Although several papers have been published dealing with steel slag use in blended cement, few have addressed the grinding aspect and little careful laboratory investigations of steel slag grinding phenomena seem to have been done to date. It is considered that the energy consumed in relation to calcining and grinding of raw materials can be saved when using steel slags as active additive materials. However, several questions exist as to the degree of grindability of BOS slag and how it compares with OPC clinker and other materials, the suitable mill feeding size and the overall assessment of grindability.

It is well known that steel slag contains similar mineral composition to that of clinker; however, because of composition fluctuations, the slag may become unstable due to excess free CaO. GBFS possesses hydraulic properties that can only be activated in the presence of an existing basic or sulfate activator such as CaO or $CaSO_4$ (Asaga, Shibata, Hirano, Goto, & Daimon, 1981; Duda, 1987; Narang & Chopra, 1983). Steel slag contains excess CaO that could constitute this activator. These factors comprise the premise for using steel slag as a component material for SSBC manufacture. Experiments have proven that the combined use of steel slag with GBFS and/or OPC clinker can balance the composition fluctuations in the steel slag and some CaO in the steel slag can be absorbed by GBFS, thereby preventing the occurrence of instability of SSBC specimens.

Despite differences in respective quantities of the chemical and mineral constituents that exist between steel slag and OPC clinker, steel slag can be considered comparable with OPC clinker. These differences do not affect the potential use of steel slag as an active material.

Magnetic reseparation of the steel slag can improve the efficiency of intergrinding steel slag and OPC clinker by about 50% compared with intergrinding OPC clinker and nonmagnetically reseparated steel slag. The grindability of mixtures of steel slag and OPC clinker depends on the relative content and initial pregrind size of the steel slag. No decrease in grindability was measured when less than 20% of 2.36–4.75 mm steel slag was added to the OPC clinker.

The magnetically reseparated steel slag grinds finer than steel slag without magnetic reseparating.

Magnetic reseparation of steel slag results in improved grinding with the material exhibiting grindability intermediate between that of steel slag and OPC clinker after the same time of grinding.

13.4.1 Stability and other properties of slag blended cement

13.4.1.1 Stability

SSBC paste specimens were inspected when cured. No cracking on the surface of the samples was observed under standard curing conditions for a period of 60 days. Two specimens of each mix, cured in water for 28 days, were treated by saturated steam at 3 bar (137°C) for 50 min. The treatment cycle consisted of 50 min presoaking (temperature and pressure build-up), 50 min soaking time, followed by 50 min cool down period with gradual pressure reduction. Specimens from mixes of BOF slag 1 and 2 exhibited no cracking even after 100 min of treatment under the same pressure. The treatment condition is more harsh than that for testing the effect of MgO on OPC. This indicates that the addition of 10% OPC clinker can effectively prevent the occurrence of instability in SSBC (Wang, 1992).

13.4.1.2 Characteristics of SSBC

Characteristics of SSBC, based on commercially available steel–GBFS and gypsum blends (Sun & Yuan, 1983), containing 45% BOS slag, 45% GBF slag, 10% gypsum, by weight, are

Specific gravity: 3.0–3.4;
Unit weight: 900–1100 kg/m^3;
Setting time: initial setting time > 45 min; final setting time < 24 h;
Ratio of early to late strength: the SSBC has higher strength ratio compared with OPC, strength of SSBC at 1 year increases by 152–166% of that at 28 days (45.8 MPa at 28 days), whereas for OPC it takes 5 years for the strength to reach 150% of 28-day strength;
Dimensional stability: SSBC has low expansion. Expansion is 0.109% at 10 days; 0.14% at 14 days. Expansion essentially remains constant after 14 days;
Wear resistance: The wear resistance of steel slag cement is twice that of PC;
Carbonation resistance: After carbonation of the SSBC samples in 50–60% CO_2 atmosphere the strength increases by 20%.

13.4.2 Grindability of slag

Grindability is of major importance in the manufacture of slag blended cement. In terms of grindability, BFS is slightly more abrasive than clinker and cogrinding has to be performed with care (Alanyali et al., 2009).

The laboratory results are inconclusive in determining the efficiency of intergrinding steel slag and OPC clinker. Lowrison (1974) reported the Bond index for grindability of different materials: corundum 30–35; silica sand 16; cement clinker 15; slag 11 (type of slag not specified).

In a SSBC pilot study conducted by the author, although the weight retained on the 75 µm sieve for steel slag was higher than that for OPC after grinding, about 30% of the amount of coarse OPC particles still remained as unground particles in the ball mill. This phenomenon did not occur for the steel slag. Judging from the strength of OPC and steel slag, the hardness of steel slag should be close to that of OPC. The main reasons why steel slag may be considered to be difficult to grind may be due to the incorporation of iron scrap. In the laboratory experiments reported here, about 22% by weight of steel slag was attracted by the reseparation magnet, the separated slag particles consisting mainly of fine iron particles. Nonremoval of these materials would make the slag much more difficult to grind. Magnetic reseparation is absolutely necessary, if the steel slag is to be used for manufacture of SSBC, and to ensure that the very fine particles are removed because most of them contain impurities and iron, which affects the quality of the SSBC and decreases the grindability.

Although the grindability of steel slag is rarely covered in the literature, it is of major concern in the manufacture of SSBC. Preliminary work was carried out by using a laboratory ball mill to investigate the grindability of the steel slag and OPC clinker when ground separately and interground for periods of 30 and 60 min. OPC clinker having particle sizes in the range of 8.0–13.2 mm and steel slag having particle sizes in the range of 8.0–13.2 mm and 2.34–4.75 mm were used in the test. Comparative tests were performed for magnetically reseparated steel slag, ordinary steel slag, and OPC clinker. The degree of grindability was assessed by particle size distribution. Results of 30 min grinding have similar trends.

The laboratory grinding tests indicated that

(i) when ground separately, OPC clinker grinds finer than steel slag for the same time of grinding;
(ii) the magnetically reseparated steel slag grinds finer than steel slag without magnetic reseparating;
(iii) magnetic reseparation of steel slag results in improved grinding with the material exhibiting grindability intermediate between that of steel slag and OPC clinker after the same time of grinding; and
(iv) when 2.36–4.75 mm particle size steel slag is interground with OPC clinker, the grindability of the composite is better than that of OPC clinker provided that the content of steel slag in the composite is not greater than 20%.

Selective use and quantification of steel slag having suitable properties are important aspects for manufacture of SSBC. The slag should be magnetically reseparated prior to grinding for SSBC. Both too fine and too coarse particles are not suitable for SSBC. If particles are very fine, impurities such as dust might be incorporated; if they are too coarse, additional crushing will be necessary and, thus, more energy will be consumed. Particle sizes within a certain range, probably 2–15 mm, should be selected for SSBC manufacture. The incorporation of steel slag with particle size below 5 mm can benefit the grinding of OPC clinker. Other particle size materials should be used for other applications (eg, road base, etc.). The addition of steel slag, at content levels of up to 20% of total solid material, is suggested as optimum with regard to stability, economy, and strength of the blended cement.

13.4.3 Quantification criterion for steel slag use in blended cement manufacture

It is well known that steel slag contains similar mineral composition to that of OPC clinker; however, because of composition fluctuations, the slag may become unstable due to excess free CaO. GBFS possesses hydraulic properties that can only be activated in the presence of an existing basic or sulfate activator such as CaO or CaS (Asaga et al., 1981; Duda, 1987; Narang & Chopra, 1983). Steel slag contains excess CaO that could constitute this activator. These factors comprise the premise for using steel slag as a component material for SSBC manufacture. Experiments have proven that the combined use of steel slag with GBFS and/or OPC clinker can balance the composition fluctuations in the steel slag and some CaO in the steel slag can be absorbed by GBFS, thereby preventing the occurrence of instability of SSBC concrete.

BOS slag is produced during steelmaking by the basic oxygen process. The manufacture of steel involves the removal of excess quantities of carbon and silicon from the iron by injection of oxygen and the addition of small quantities of other constituents that are necessary for imparting special properties to the steel. A lime or dolomite flux is used that combines with the oxidized constituents to form a slag. BOS slag is decanted off from the surface of the molten steel and is normally cooled slowly, by air-cooling or water quenching, in pits or bays prior to being dug and transported to holding areas.

Despite differences in respective quantities of the chemical and mineral constituents that exist between steel slag and OPC clinker, steel slag can be considered comparable with OPC clinker. These differences do not affect the potential use of steel slag as an active material. The main differences are summarized in Table 13.6.

Table 13.6 **Comparison of the chemical composition of steel slag and Portland cement clinker**

	Chemical composition (% by weight)				
Materials	**CaO**	**Al_2O_3**	**SiO_2**	**FeO/Fe_2O_3**	**P_2O_5**
Steel slag	>35	<5	<20	<25	Trace
Portland cement clinker	<60	4–10	18–24	<5	None

The existing forms of the chemical composition in steel slag and OPC clinker are

(i) CaO in steel slag mainly forms C_2S, C_3S and merwinite (C_3MS_2), and in OPC clinker it forms C_3S, C_2S, C_3A and C_4AF.
(ii) Aluminum oxide (Al_2O_3) content in steel slag exists in solid solution. In OPC clinker, Al_2O_3 forms calcium aluminate and calcium aluminoferrite.
(iii) The total amount of iron oxide in steel slag exists in the form of FeO and Fe_2O_3, but mainly in the form of bivalent FeO. Normally, FeO accounts for about 70% of total iron content.

13.4.3.1 Addition criterion for steel slag in SSBC

The addition of steel slag to the OPC clinker has to be considered in terms of f-CaO content of steel slag, total f-CaO content of SSBC, and grindability. From the results of grindability, it is known that, from grindability considerations, the optimum addition of steel slag is below 30% of total weight of SSBC (BOS slag and OPC clinker). In addition, the total f-CaO content of SSBC should be less than 2%, which is an acceptable limit for OPC and there should also be a relationship controlling the addition of BOS slag depending on its f-CaO content. From this criterion it can be shown that, provided the relative content of steel slag is controlled, steel slags with a high free calcium oxide content can be used as an ingredient of SSBC. These steel slags would not normally be suitable for other engineering applications. The addition criterion, in terms of f-CaO content, is as follows:

$$\text{f-CaO in SSBC} < 2\% \text{ i.e.} \tag{13.1}$$

$$\left[F_s \times (1 - C_o) + F_c \times C_o\right] \times 100 < 2\% \text{ or} \tag{13.2}$$

$$S_c = 1 - C_o < (2\% - F_c \times C_o) / F_s \text{ or} \tag{13.3}$$

$$F_s < \left[2\% - F_c \times C_o\right] / S_c \tag{13.4}$$

where F_s is the free CaO content in steel slag (by w/w%); C_o is the content of OPC clinker (by w/w%); F_c is the free CaO content in OPC clinker (by w/w%); and S_c is the content of BOS slag (by w/w%).

This can be illustrated by the following two examples:

(i) For a given steel slag with 1.6% f-CaO content and OPC clinker with 0.5% f-CaO, if a mixture comprising 20% BOS slag and 10% OPC clinker is interground, the resultant SSBC will be volumetrically stable if f-CaO < 2%. Substituting the values into Eq. (13.2), the f-CaO content of SSBC is 0.72%. This is less than 2%, and therefore the mix is of acceptable stability.

(ii) A SSBC contains 10% OPC clinker, with 0.5% f-CaO, and 20% BOS slag. What is the maximum allowable f-CaO for the BOS slag? Substituting into Eq. (13.4) gives an answer of 11%. This means that steel slag containing < 11% f-CaO can be used in SSBC.

13.5 Other cementitious applications of slag

Ground steel slag can be used to make paving blocks to reduce the cost of cement. The main cost incurred in the production of concrete paving blocks is the cost of the cement-based binders. In addition, there is the environmental cost of quarrying and processing of these primary materials. Gypsum-based industrial by-products can be used as alternative sources of cement. These materials have little or no production cost and their reuse negates the need for disposal, offering a more sustainable material for the production of paving blocks. Laboratory trials have investigated the properties of red gypsum, derived as a coproduct associated with titanium dioxide manufacture, mixed with pulverized fuel ash, ground GBFS, lime, and basic steel slag. An assessment of samples was made using unconfined compressive strength after 28 days curing. It was found that a red gypsum ground GBFS mix achieved the highest unconfined compressive strength (up to 39 MPa) and was selected for further investigation. Two binders, composed primarily of red gypsum and ground GBFS, were mixed with sand and pea gravel to make 100 mm concrete cubes and compared with PC for uniaxial compressive strength, stiffness, and workability. The red gypsum-based binder compared favorably with PC, indicating that there is potential to integrate red gypsum into concrete block mixes.

13.6 Summary

BOF slag exhibits good hydraulic activity when blended with GBFS and gypsum and with or without OPC clinker addition even though the fineness of grind, achieved in a laboratory ball mill, was not as high as that commonly occurring for commercially available OPC clinker.

The stability of SSBC pastes containing relatively high contents of steel slag was satisfactory when a small quantity (10%) of OPC clinker was added. Good stability of SSBC in production practice should be obtained if the steel slag content is not greater than 40% and at least 10% OPC clinker is incorporated in the blend.

No significant differences in compressive strength were exhibited for SSBC pastes containing recently produced steel slag and those containing aged steel slag, with the stability of both being acceptable when 10% OPC clinker was added.

Magnetic reseparation of the steel slag can improve the efficiency of intergrinding steel slag and the OPC clinker by about 50% compared with intergrinding OPC clinker and nonmagnetically reseparated steel slag. The grindability of mixtures of steel slag and OPC clinker depends on the relative content and initial pregrind size of the steel slag. No decrease in grindability was measured when less than 20% of 2.36–4.75 mm steel slag was added to the OPC clinker.

Questions

13.1 What are the raw materials for making Portland cement?
13.2 What are the major minerals in Portland cement?
13.3 What are the major of processing methods in Portland cement manufacture?
13.4 How to compare the energy consumption for cement to other manufacture industries?
13.5 Compare the hydraulic activity of ferrous, nonferrous, and nonmetallurgical slags.
13.6 Describe the BFS cement manufacture process.
13.7 Describe the steel slag cement manufacture process.
13.8 How to activate hydraulic activity of copper slag?

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Case studies on slag utilization

14

14.1 Introduction

Three case studies are presented in the following sections. The first case study is about the use of electric arc furnace (EAF) slag in Egnatia Odos, the 670 km project near Thessaloniki, Greece. Egnatia Highway is the greatest road construction project in Greece. The €5.9 billion project extending from west to east in mainland Greece was completed in 2009. Safety being of major importance combined with cost–effective solutions resulted in the adaptation of a new specification for the skid-resistant surface course. The new specification, closely related to Spanish standards, involves a 25 mm, well open-graded mixture of fine sand and coarse aggregates of the same origin, using modified asphalt binder.

This case study is a result of close cooperation between the managing company of the highway, Egnatia Odos SA, and the sole producer of EAF aggregates in Greece, AEIFOROS SA, and describes the findings from two perspectives. The first one, being the view of the administrating body, summarizes the results of the measurements such as SRV, LA, macrotexture depth, water penetration, effective binder content, all compared to the original mixture studies. Comparison is made to similar courses with natural aggregates of igneous origin. In advance, the produced baghouse fines (normally of no use in asphaltic concrete) were used as mineral filler of self-compacting concrete (SCC).

The second case study presents the use of EAF slag aggregate for stone column ground stabilization in Saudi Arabia by MultiServ, South Yorkshire, the United Kingdom.

Certain ground conditions do not have sufficient load-bearing capacity to support suitable foundations for construction of buildings and structures. In the Eastern Province of Saudi Arabia, the natural surface conditions often fall into this category and the soil needs to be stabilized to establish suitable foundations for construction work.

One method adopted for ground stabilization is the construction of stone column piling using the vibrofloatation method. This case study outlines the procedures that have been developed to assess the suitability of a specific source of EAF slag aggregates (from the MultiServ operation in Al Jubail, Saudi Arabia) for this application. Factors taken into consideration are the mechanical properties of the slag and the potential impact on the environment.

The third case study concerns the use of nickel slag in highway construction. Air-cooled (AC) nickel slag is evaluated for highway construction applications as an aggregate in hot-mix asphalt (HMA). The AC nickel slag is a liquid by-product of nickel production that is solidified under ambient conditions. The laboratory evaluation program, which was carried out to determine the characteristics of the AC nickel slag, included physical and mechanical properties testing, petrographic examinations, and mixture designs. Accelerated laboratory testing was completed on the mixtures by using an asphalt pavement analyzer (APA) to assess their performance characteristics.

The Utilization of Slag in Civil Infrastructure Construction. http://dx.doi.org/10.1016/B978-0-08-100381-7.00014-8

Additional testing included autoclave disruption tests for free lime and free magnesia, and chemical/mineralogical analyses, polished stone value (PSV) and aggregate abrasion value (AAV). This study indicated that suitably processed nickel slag is environmentally, mineralogically, and physically stable. From the accelerated laboratory testing completed, it is concluded that the AC nickel slag is suitable for use as coarse and fine aggregates in HMA. The utilization of nickel slag in highway construction is also presented in this case study.

14.2 Using EAF slag in Egnatia Highway construction

Egnatia road or Via Egnatia dates back to Roman times, one of the two most important roads leading to the capital Rome. Via Egnatia part of the larger path of the Via Traiana that, via the port of Gnaphia, crossed present-day Greece to the Evros Rive. The Via Egnatia ran through Dyrrachium, Lychnidos, Heracleia, Edessa, Pella, Thessaloniki, Amfipolis, Filippoi, Topeiro, Maximianoupolis, and Traianoupolis.

Originally built in 146 and 120 BC following the path of a pre-Roman road, stretched from Evros in eastern Greece to western alpine landscapes, being the military road during Roman, Byzantine, and post-Byzantine times. The name *Egnatia* was given to the entire road (ie, from Rome to Constantinople) in honor of the Roman proconsul Gnaeus Egnatius who built it (Egnatia Odos, 2015).

This study presents the technical data of the surfacing for the part 10.1–11.2 of Egnatia highway and specifically for the part between Nymfopetra and Rentina Junction. The excess filler from the slag sand was further used for SCC mix.

14.2.1 Background information

Since 1984, feasibility studies of the largest road construction project in Greece had been conducted and developed to reconnect, through major road construction, eastern and western Greece on the traces of the ancient Via Egnatia. Not only did morphological and topological difficulties exist, especially in the Alpine environment of the Pindos mountain range, but so did vast civil engineering problems including landslides, enormous backfilling, and tunnels and bridges through intense seismogenous zones (Fig. 14.1).

It was not until the mid-1990s that construction began through the plains of eastern Greece. Construction of the most difficult parts of the Egnatia road was not initiated until 2005. Since then, 95% of the Egnatia road connecting Igoumenitsa in the Prefecture of Thesprotia to Kipi in the Prefecture of Evros was constructed with a remaining 40 km then due by the beginning of summer 2009.

The Egnatia Motorway is crossing three regions, namely, from east to west Thrace, Macedonia, and Epirus starting from the Igoumenitsa Port, which provides links by boat to Italy, and ending in Kipi in Evros (the Greek–Turkish border).

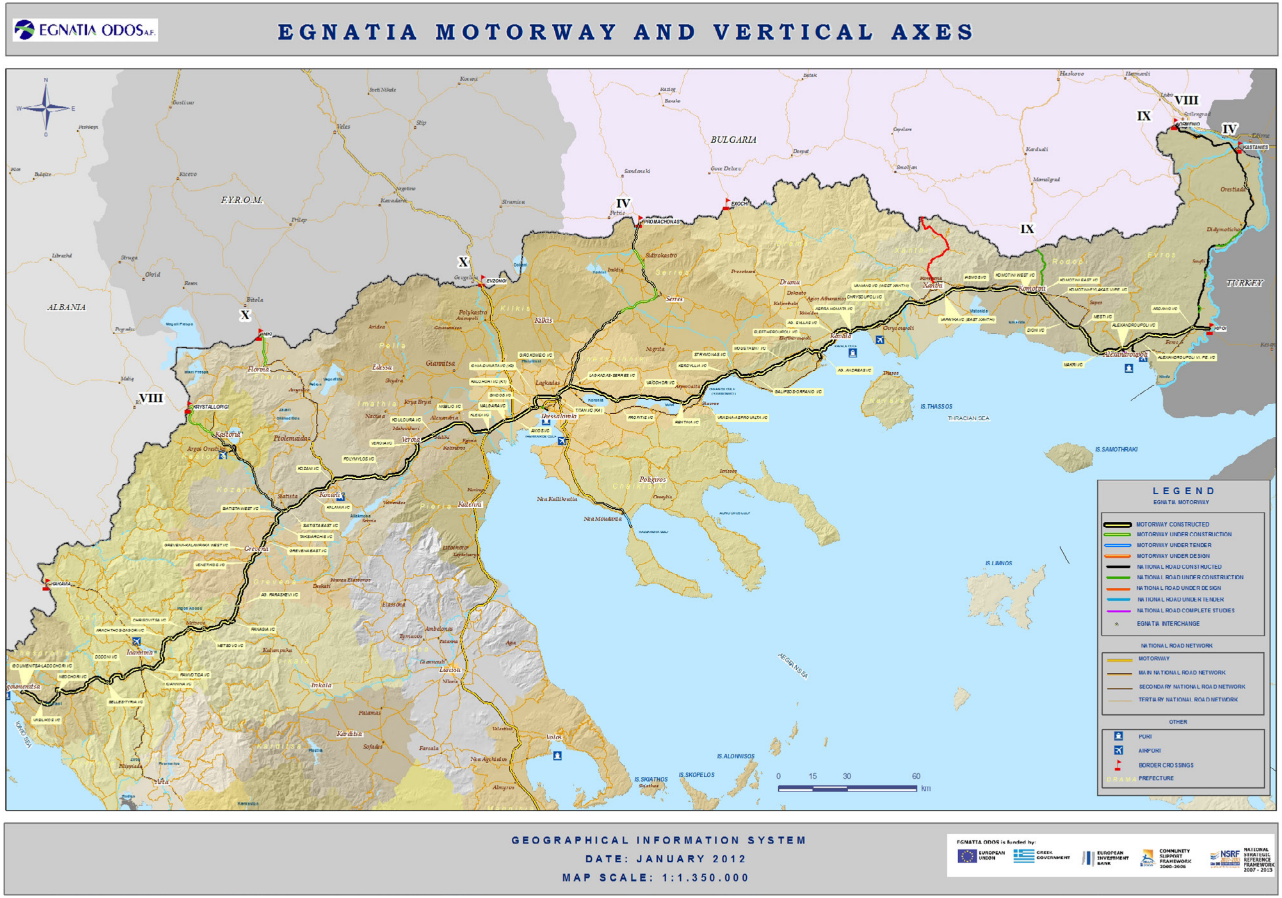

Fig. 14.1 Map of Egnatia road (Hellenic MOE, 2010).

Table 14.1 **Identity of Egnatia**

Stretching	From Igoumenitsa in the Prefecture of Thesprotia to Kipi in the Prefecture of Evros
Total length	670 km
Linked ports	Igoumenitsa–Thessaloniki–Kavala–Alexandroupoli
Linked airports	Ioannina–Kastoria–Kozani–Thessaloniki–Kavala–Alexandroupoli; 332 towns and villages
Proposing and financing	Archaeological excavations, protection of monuments, environmental protection works (biotopes, etc.)
Technical characteristics	Dual carriageway of international standards with two traffic lanes per direction, a central reserve and an emergency lane

Data from Egnatia Odos (2015). *The history of the Egnatia motorway* http://www.egnatia.eu/page/default.asp?la=2&id=23.

On a national level, the Egnatia Motorway will increase investments in sectors like transport (eg, new freight centers), industry, and tourism. It will play an important role as a major development axis in northern Greece.

On a European level, the motorway links the major industrial centers of the West with those in the East.

Table 14.1 illustrates the major features of the project.

14.2.1.1 Adaptation to bituminous surfacing

Following the major innovations in construction level, EGNATIA ODOS SA, the company responsible for the supervision of construction and operation of Egnatia Highway, adopted a 25 mm thin HMA surfacing, according to article ST6 of the Official Body Technical Specification where both gravel and sand must be from the same hard aggregate (Hellenic MOE, 2010), which in the case studied is EAF slag processed by the recycling company AEIFOROS SA.

14.2.2 Materials, mix design, and placement

The main characteristic of the 25 mm open-graded surfacing is the air voids (6–15%) that allow surface runoff of rain water and prevention of spraying. The sufficient macrotexture depth in combination with skid resistance of the aggregates results in (i) decrease of noise and (ii) prevention of blurring from the reflection of light on the surfacing.

The final course guarantees minimum aquaplaning with a major decrease of spraying during heavy rain conditions, which can raise visibility and thus safety issues during motorway operation (Kechagia, 2004).

The drawbacks of this specification are (i) greater oxidization of asphalt; (ii) risk of binder efficiency in cases of improper mix; (iii) decreased life span in comparison to close-graded mixes; (iv) fines and dust filling air voids reducing beneficiary effects of increased macrotexture; (v) necessity of close-graded underlying layer with sufficient traverse gradient; and (vi) reduction of bearing capacity in comparison to thicker 45 mm skid-resistant surfacing of normal practice (Hellenic MOE, 2010).

Table 14.2 Grain size distribution for EAF slag

Sieve size (mm)	Specified percentage passing (%)	EAF slag percentage passing (%)
Coarse aggregates		
14	100	100
10	99–85	87.9
8	37–62	40
6.3	1–15	4.7
4	0–5	1.8
0.6	0–2	0.6
Fine aggregates		
6.3	100	100
2	99–85	85.4
0.5	40–60	51.5
0.063	11–16	18.3

Data from Lykoudis, S., & Liapis, I. (2010). Egnatia Odos, the 670 km project and EAF slag. In: *Proceedings of the 6th European slag conference, October 20–22, Madrid, Spain*.

The first three drawbacks are solved through the use of modified bituminous binder, while the rest are not considered sufficient to reduce the effectiveness.

14.2.2.1 Aggregates (coarse, fine, and filler)

According to specification ST6 of technical specifications, both coarse and fine aggregates must be crushed and of the same origin. The grain size distribution as well as the upper and lower limits of the specification are presented in Table 14.2.

For filler aggregates (passing 63 μm), limestone was used. Very fine limestone sand with 16% filler was used for base and subbase courses and as such 7–8% of it was rejected and included in the skid-resistant mix (Table 14.3).

Table 14.4 presents the mechanical and physical properties of the aggregates in the mix.

Table 14.3 Limestone filler distribution

Sieve size (mm)	Specified percentage passing (%)	Limestone filler percentage passing (%)
Filler aggregates		
0.5	100	100
0.063	70–100	100
Methylene blue value (MB_F)	<1	0.3

Data from Lykoudis, S., & Liapis, I. (2010). Egnatia Odos, the 670 km project and EAF slag. In: *Proceedings of the 6th European slag conference, October 20–22, Madrid, Spain*.

Table 14.4 **Physical and mechanical properties of the aggregates**

Test	Result	Specification
Resistance to fragmentation (L.A.) %	15.06	ASTM C131/89
Water absorption of coarse aggregate %	1.16	AASHO T-85
Water absorption of filler aggregate %	1.15	AASHO T-85
Water absorption of fine aggregate %	1.50	AASHO T-85
Sand equivalent (S.E.)	70	AASHO T-176
Specific weight of coarse aggregate (g/cm^3)	3.268	AASHO T-84 & T-85
Specific weight of filler (g/cm^3)	2.263	AASHO T-84 & T-85
Specific weight of fine aggregate (g/cm^3)	3.167	AASHO T-84 & T-85
Resistance of wear using $MgSO_4$ for coarse aggregate %	2.91	AASHO T-104-99
Resistance of wear using $MgSO_4$ for fine aggregate %	3.612	AASHO T-104-99
Aggregate crushed value %	12	ΕΛΟΤ EN 1097.02
AAV %	2.80	BS 812.113-1991
Flakiness index (FI) %	9.77	BS 812.105.1:1989
Elongation index (EI) %	11.32	BS 812.105.1:1989
Resistance to polishing (PSV)	64	EN 197.80
Methylene blue	5.00	EN 933.09-1999
Micro-Deval	9	EN 1097-1

Data from Lykoudis, S., & Liapis, I. (2010). Egnatia Odos, the 670 km project and EAF slag. In: *Proceedings of the 6th European slag conference, October 20–22, Madrid, Spain.*

14.2.2.2 Bituminous binder

The binder used for this project was polymer modified asphalt with 4% SBS polymer type P 25/55 according to EN 14023 (Table 14.5).

14.2.2.3 Mix design

The final mix design contains 75% EAF 6.3–10 mm slag, 20% 0–2 mm EAF slag sand, and 5% limestone filler (all percentages per weight of aggregates). Table 14.6 presents the mix design characteristics. The Marshall samples were compacted with 50 blows on a compaction pedestal.

The HMA was produced in a conventional hot mix plant. The production process did not differ from the one followed in conventional mixes. The only difference was the heating temperature for the asphalt binder and the mix with the aggregates. These temperatures were 165–175°C for the asphalt and approximately 170°C for the mixture.

14.2.2.4 Placement

The produced mix was transported to the job site, a 5-km distance, where it was placed with conventional HMA paver (Fig. 14.2).

It should be noted that mainly due to high air temperature at the time of spreading (approximately 28–30°C in August), no particular temperature decrease was observed (5–10°C) (Lykoudis & Liapis, 2010). After further cooling of an additional 10–15°C

Table 14.5 Binder properties

Test	Result	Specification
Flash point (°C)	>230	AASHO T-48
Penetration at 25°C	46	AASHO T-49
Softening point (°C)	77	AASHO T-53
Ductility at 25°C cm	>100	AASHO T-51
Solubility in CCL4 %	99.76	AASHO T-45
Elastic recovery (25°C) %	92	ASTM D6084–97
Viscosity acc. BROOKFIELD 160°C cPs	421	ASTM D4402–95
Fraas point (°C)	−13	EN 12593-1999
RTFOT tests		
Penetration at 25°C	42	AASHO T-49
Softening point (°C)	79	AASHO T-53
Elastic recovery (25°C)	73	ASTM D6084–97
Mass change (%)	0.85	

Data from Lykoudis, S., & Liapis, I. (2010). Egnatia Odos, the 670 km project and EAF slag. In: *Proceedings of the 6th European slag conference, October 20–22, Madrid, Spain*.

Table 14.6 Mix design characteristics

Property	Specification limit	Result
Bulk density of compacted asphalt mix (g/m^3)	–	2.626
Max theoretical density of compacted asphalt mix acc. Rise (g/m^3)	–	2.905
Air voids in compacted mix (%)	6.0–15.0	9.6
Voids in the aggregates % (VMA)	–	22
Voids filled with binder % (VFB)	–	56.4
Bulk density of aggregate mix (g/m^3)	–	3.198
Active specific weight of mix (g/m^3)	–	3.217
Total specific weight of mix (g/m^3)	–	3.228
Specific weight of binder	–	1.02
Active binder content (%)	–	4.81

Data from Lykoudis, S., & Liapis, I. (2010). Egnatia Odos, the 670 km project and EAF slag. In: *Proceedings of the 6th European slag conference, October 20–22, Madrid, Spain*.

compaction begun. The number of passes of 8- to 10-tonne rollers was determined during construction and 4–6 passes were made (Fig. 14.3).

14.2.3 Testing verification

During construction, representative samples were taken for inspection (Kechagia, 2004) of (i) grain size distribution for the mix of aggregates; (ii) percentage of binder; (ii) percentage of air voids; and (iv) penetration and softening of the binder.

Fig.14.2 Asphalt paving.

Fig. 14.3 Mix compaction.

The samples were taken from the compacted mix. At the same time macrotexture depth and penetration measurements were carried out in situ.

Indicatively, the characteristic results for macrotexture depth were 1.8–2.7 mm (Fig. 14.4), while penetration was 0.20 cm/s up to 0.40 cm/s (Fig. 14.5).

14.2.4 Use of excess EAF filler as mineral filler in SCC

SCC is the type of concrete that, due to its own gravity and rheological nature, can fill any type of form work and obtain the appropriate compaction with no additional vibration due to low viscosity and great workability. The main feature of SCC is the

Fig. 14.4 In situ testing of macrotexture depth.

Fig. 14.5 Penetration testing.

special fluidity of the mix in connection to the stability, the latter being a measurement of resistance to segregation of the materials, both dynamic (during transport) and static (after placement). This advanced concrete is targeted to improve specific aspects of normal practice.

According to experts SCC is the greatest evolution in the field of concrete technology in the last 50 years. Compared to traditional practice, the mix design contains greater percentages of fines and filler aggregates, as well as admixtures like plasticizers and viscosity modifiers (VMA).

The greatest problem for the production of SCC was the lack of fine aggregate sources. During the production process of asphalt concrete described previously, excess EAF slag filler was collected in baghouse filters. The suitability of slag filler as mineral filler is studied in this section. The chemical composition of slag filler is presented in Table 14.7. X-ray diffraction analysis was used to identify the composites and no chemical change was observed.

After multiple trial mixes, the best mix was chosen (Table 14.8), the properties of which in fresh and hardened state are presented in Tables 14.9 and 14.10.

During the lab testing (Slump Flow, L—Box, V—Funnel, Figs. 14.6–14.8) and application the resulting mix presents all the properties of SCC and as such it was applied successfully during construction.

Table 14.7 Chemical composition of filler

Sample	Specific weight	Blaine	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
EAF filler	3.20	2372	65.22	16.65	2.00	5.38	0.58	0.12

Data from Lykoudis, S., & Liapis, I. (2010). Egnatia Odos, the 670 km project and EAF slag. In: *Proceedings of the 6th European slag conference, October 20–22, Madrid, Spain*.

Table 14.8 Best mix design

Materials	Percentage (kg/m^3)
Portland cement II 42,5 (origin TITAN)	400
Total water	220
EAF slag filler	80
Coarse aggregates 4/10	680
Sand 0/4	890
VMA	0.2
HWRA	5.5
Stabilizer	0.9

Data from Lykoudis, S., & Liapis, I. (2010). Egnatia Odos, the 670 km project and EAF slag. In: *Proceedings of the 6th European slag conference, October 20–22, Madrid, Spain*.

Table 14.9 Properties of fresh SCC

Time	Slump flow	V-funnel	L-box
t_0	71/72	5	1
t_{30}	70/71	6.5	1
t_{60}	68/64	7	0.8
t_{90}	60/62	12	0.75

Data from Lykoudis, S., & Liapis, I. (2010). Egnatia Odos, the 670 km project and EAF slag. In: *Proceedings of the 6th European slag conference, October 20–22, Madrid, Spain*.

Table 14.10 Properties of hardened SCC

Age of sample	Ultimate compressive strength c_u (MPa)
16 h	9.3
24 h	11.7
3 days	28.1
7 days	34
28 days	42.5

Data from Lykoudis, S., & Liapis, I. (2010). Egnatia Odos, the 670 km project and EAF slag. In: *Proceedings of the 6th European slag conference, October 20–22, Madrid, Spain*.

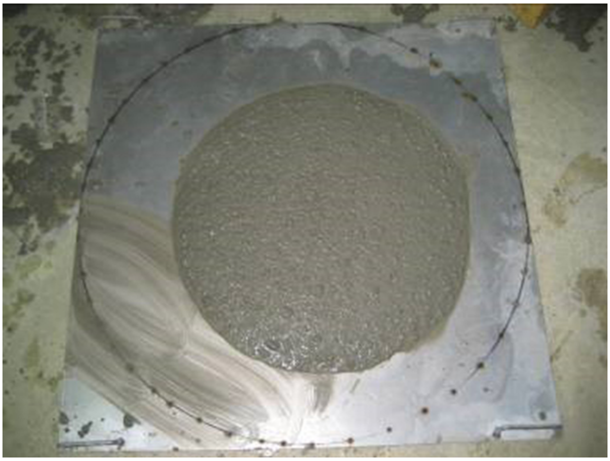

Fig. 14.6 Slump flow.

14.2.5 Summary

Egnatia road, a multibillion-euro revival of ancient Via Egnatia is being realized. A closed motorway, fully developed to meet the highest safety standards, it had to overcome exceptional engineering problems. Innovations ranging from long-span bridges and tunnels in a seismogenous area down to the application of a 25 mm, close-graded

Fig. 14.7 L-box test.

Fig. 14.8 V-funnel test.

surfacing had to be adopted. Innovative methods most of the time necessitate innovative materials, which in the case of the thin surfacing, was EAF slag.

In conclusion, after the preliminary testing and field application of the thin bituminous mixture,

(i) Initial testing and application of the asphaltic concrete consisting solely of slag aggregates can be considered a success giving the final surfacing all the required properties.

(ii) In addition, the physical, mechanical, and chemical consistency of EAF slag played an important role in simplifying the bituminous mix production process. It is yet left to examine the behavior of the skid-resistant course through time due to extreme weather conditions of the area. Long-term experience in mixes with similar characteristics (4 mm asphaltic concrete, which is the normal practice) leads us to believe that this is not something to be expected.

(iii) Finally, excess filler of slag sand was used in SCC, both in laboratory trial mixes and in field applications. Initial results show high early strengths with an increase in the weight of the concrete.

14.3 Using steel slag aggregate for stone column ground

Construction requires stable ground in which to create secure foundations, and these normally take the form of relatively shallow components, such as strip foundations, pads, or raft foundations. However, there are certain ground conditions where load-bearing soil extends down to a considerable depth and the use of traditional foundation methods become uneconomical. Such situations require deep stabilization to improve the load-bearing capacity. One method of deep stabilization is through the formation of stone column piles, and this case study demonstrates how EAF slag has been successfully used as a replacement aggregate for this application, providing superior properties over and above the standard natural aggregate normally used for this purpose.

14.3.1 Vibrofloatation ground stabilization

Vibrofloatation is a method of ground stabilization accomplished through the formation of stone columns. The creation of these stone columns is achieved by initially forming a deep vertical shaft in the ground, using a large vibrating poker with high-pressure water jets. These pokers can be inserted to depths ranging from 5 to 15 m. In addition to creating a hollow space in the ground, they also provide densification of the surrounding soil by high-frequency vibration of the poker. The resulting hole is filled with stone of a specific size fraction, or a combination of size fractions, and compacted using the vibrating poker (see Fig. 14.9). The poker itself uses either compressed air or electric motors to drive eccentric weights for the vibration mechanism. It is usually 300–400 mm in diameter and can weigh up to 4 tonnes (4.4 tons). The diameter of the final column will depend on the stiffness of the soil but can be up to 1 m wide.

14.3.2 The history of EAF slag use

EAF steel slag, from the MultiServ operation within the Haddeed Steelmill in AL Jubail, has been used in vibrofloatation ground stabilization from November 1995. Over that time, 21 construction projects have been supplied with over 970,000 tonnes of steel slag aggregate.

Before any of the steel slag was accepted as an approved aggregate for this application, it had to undergo a rigorous testing program to ensure conformity. The testing program was designed such that both mechanical and physical properties were evaluated as well as the potential environmental impact of the material.

14.3.3 Contracts and volumes

Steel slag has been used for the construction of stone columns, in the size fraction 25/75 m (for wet applications) and 19/37 mm (for dry applications), in Saudi Arabia since 1995.

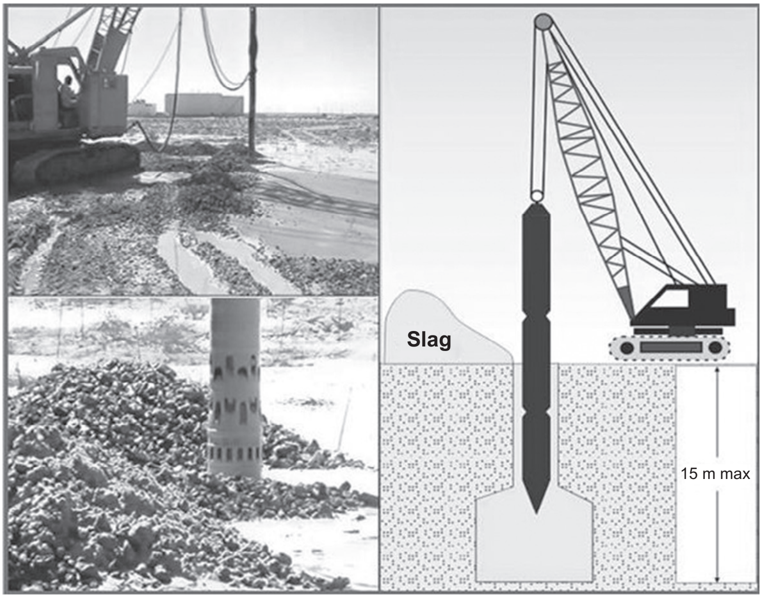

Fig. 14.9 Scheme of the vibrating poker with high-pressure water jets.

Table 14.11 indicates the quantities of steel slag aggregate supplied over this period and identifies some of the projects where the slag has been involved in stone column ground stabilization.

It can be seen from Table 14.11 that the market grew as confidence in the use of the slag aggregate increased, peaking in 1998. In 2001, MultiServ was awarded the contract for handling the molten slag from the pits at Haddeed. At this time the handling methods changed to reduce processing costs through the crushing, screening, and metal separation plant. As a result, the volume of larger-sized slag required for the ground stabilization market diminished and an accumulation of old stock, not previously used, was processed to meet demand. This is the reason for the fluctuation in sales during this period.

The current molten slag handling technique will not generate the sizes of slag to match the demands for this particular application, but the practice can be altered to enable the production of such sizes if notification of a contract is received. A balance has to be struck between meeting demand for one particular market, having a requirement for a very specific size fraction, and the full utilization of all slag generated by the mill. The smaller size fractions produced from this unit are supplied to the road construction market as aggregates for unbound base materials and also for asphalt surfacing products. Having control of the liquid slag makes it possible to affect the actual size of the raw feed to the processing plant and therefore influence the volumes of various sized products.

Prior to the EAF slag being accepted for the use as an aggregate for ground stabilization, it had to be assessed for suitability in terms of its mechanical and physical properties, but also for properties that might affect the environment. It is usual for this work to be conducted by the consulting engineer in charge of the contract and because

Table 14.11 The use of steel slag aggregate for stone column ground stabilization

Year	Tonnes supplied	Project	Location
1995	30,000	Toy Town	Al Khobar
1996	46,000	Nama Caustic Soda Prilling	Industrial City Jubail
		Austrian Energy Arabia	Industrial City Jubail
1997	21,000	Inma	Al Khobar
1998	395,000	Polester Resin	Industrial City Jubail
		Tayf-Ibn-Hayyan	Industrial City Jubail
		Sahaba Mosque	Rahima
		SWCC	Al Khobar
		United Gulf Steel	Industrial City Jubail
		Scado Buildings	Al Khobar
1999	36,000	Ghazian Power Plant 2	Ghazian
2000	280,000	SABIC Fire Training Center	Industrial City Jubail
		Jeraisy Office	
2001	131,000	Flat Product Facilities, Hadeed Steel	Industrial City Jubail
		Tamimi Supermarket	Dammam
		Al Muhaidib Complex	Al Khobar
		Modecor	Industrial City Jubail
2003	32,000	Sadaf Power Plant	Industrial City Jubail
		Giant Sores	Dammam
Total	971,000		

Data from Jones, N. (2005). The use of steel slag aggregate for stone column ground stabilization. In: *The 4th European slag conference, June 20–21, Oulu, Finland*.

of this many of the test methods and standards adopted have tended to emanate from either the United States or the United Kingdom. However, through the involvement of German companies, both German and European standards are now being used.

14.3.3.1 Physical and mechanical properties

Before a new material can be used for a particular application it needs to undergo acceptance testing to ensure conformity. Therefore, before it could be used EAF slag had to undergo a series of acceptability tests in line with those required for natural aggregate.

The required tests can be found in Table 14.12.

In Table 14.12, although there are some properties without limits specified, the parameters are recorded against end-test bearing values for information, as well as for comparison with local natural aggregates.

The particular mineral aggregate properties considered important for this type of ground stabilization are resistance to abrasion, water absorption, and grain hardness. Additional beneficial qualities include aggregate shape, angle of internal friction, and grain size distribution.

The steel slag exhibits properties that present distinct advantages over and above those of natural aggregates. A comparison of these properties can be seen in Table 14.13. From these results, it can be seen that steel slag aggregate satisfies the

Table 14.12 Mechanical and physical tests

Test	Specification	Limit
Specific gravity	ASTM C127	>2.4
Water absorption	ASTM C127	<3.0
L.A. abrasion	ASTM C131	<50
Magnesium sulfate soundness	ASTM C88	<18%
Angle of internal friction	AASHTO T23	–
Hardness	Mohs scale	–
Slake durability index	ISRM	<95
Aggregate impact value	BS 812	<10
Elongation index	BS 812	–
Flakiness index	BS 812	–
Clay lump and friable	ASTM C142	<1%
Chloride content	ASTM C114	<0.025%

Note: –, no limit.
Data from Jones, N. (2005). The use of steel slag aggregate for stone column ground stabilization. In: *The 4th European slag conference, June 20–21, Oulu, Finland*.

Table 14.13 Comparison between the physical and mechanical properties of steel slag and limestone

Property and test	Steel slag	Abuhaydriah limestone	Riyadh road limestone
Specific gravity (bulk) ASTM C127	3.75	2.56	2.59
Water absorption (%)	0.4	1.5	1.61
L.A. abrasion (% loss) ASTM C131	16	35	25
Magnesium sulfate soundness loss ASTM C88	0.9	12	12
Angle of internal friction	40–50	20–35	20–35
Hardness (Mohs scale)	6–7	3–4	3–4
Aggregate impact value BS 812	11	24	20
Elongation index BS 812	10	20	18
Flakiness index BS 812	6	25	27
Clay lump and friable particles ASTM C142	0.2	0.54	0.42
Chloride content (%)	0.017	0.024	0.021
Salke durability index ISRM	99.1	–	–

Note: –, not available.
Data from Jones, N. (2005). The use of steel slag aggregate for stone column ground stabilization. In: *The 4th European slag conference, June 20–21, Oulu, Finland*.

requirements of shape, durability, strength, interlock, and resistance to abrasion and, more importantly, is far superior to the alternate natural aggregate that is economically available.

14.3.4 Chemical and environmental tests

As the steel slag aggregate is placed below the water table, chemical analyses relating to mechanical stability and potential environmental pollution had to be undertaken prior to the first application of steel slag aggregate in 1995. Results of the tests proved positive and the slag passed as an acceptable material for this application.

As more and more contractors became involved with slag, it was deemed necessary to review the chemical nature of the current production. As a result of this, in 2003, fresh investigations were undertaken by LGA Bautechnik GmbH, Civil Engineering, who were responsible for the stabilization work.

Steel slag can contain quantities of unhydrated lime and magnesia that can potentially cause disruption through volume expansion. LGA conducted a risk assessment and the outcome (in relation to the specific type of EAF slag produced at the MultiServ operation in Al Jubail) concluded that the slag contained levels of free lime and magnesia considered to be marginal and therefore posed no swelling potential for this specific application.

To ensure that these low levels were maintained, a systematic analysis for free lime determined in accordance with EN 459-2:2001 (extracted using ethylacetoacetate and isobutanole) was required and a maximum limit of 0.5% was set.

To examine the potential to pollute the ground water, LGA also tested the slag for leachate release according to the German procedure standard; LAGA (Länderarbeitsgemeinschaft Abfall, an acknowledged official standard for environmental authorities in Germany) and in accordance with United States Environmental Protection Agency (USEPA) parameters.

The eluate was obtained according to the DIN 38414 S4, testing the aggregate in the actual size fraction used. It was not deemed necessary to grind the aggregate to smaller sizes for testing, as there was no evidence of particle size reduction or degradation in service. Results from the investigation can be seen in Table 14.14.

The conclusions from the reevaluation of the chemical properties were:

(i) The slag could be placed in the local soil and ground water without any environmental risk.
(ii) The high pH value was due to high calcium content in the raw glassy (silicate) slag, but because of the permanent silicate bond of the calcium and magnesia, these chemicals are only marginally soluble in water.
(iii) The free lime determined at 0.28% is a very low level, indicating no swelling potential for the material.

14.3.5 Summary

EAF slag from the MultiServ operation in Al Jubail has proven to be a suitable material for use in stone column ground stabilization. It demonstrates superior performance over locally available alternate natural aggregates in terms of crushing strength, water

Table 14.14 **Results of slag from an Al Jubail construction sites**

Parameter	Unit	Results of the elute from the slag	Limits of code LAGA and USEPA
pH		11.2	6.5–11
Conductivity	μS/cm	430	<500
As	mg/L	<0.01	<0.01
Sb	mg/L	<0.01	–
Ba	mg/L	0.1	<100.0
Cd	mg/L	<0.0005	<0.002
Cr	mg/L	<0.005	<0.015
Pb	mg/L	<0.005	<0.02
Se	mg/L	<0.01	<1.0
Ag	mg/L	<0.01	<5.0
Fe	mg/L	<0.05	–
Cu	mg/L	<0.05	<0.05
Ni	mg/L	<0.02	<0.04
Zn	mg/L	<0.05	<0.1
Hg	mg/L	<0.0005	<0.0002
Ti	mg/L	<0.001	<0.001
Ca	mg/L	49	–
Mg	mg/L	0.5	–
Na	mg/L	1.0	–
K	mg/L	0.2	–
Al	mg/L	3.8	–
Free lime	%	0.28	–

Note: –, no limit.
Data from Jones, N. (2005). The use of steel slag aggregate for stone column ground stabilization. In: *The 4th European slag conference, June 20–21, Oulu, Finland*.

absorption, internal friction, and durability. In relation to the chemical suitability of the slag in terms of both volume stability and leachability, the slag has proven to be totally acceptable.

As a result of its superior performance, the present four designers of these systems in Saudi Arabia specify steel slag aggregate for stone column piling.

Over a period of 9 years, 971,000 tonnes of steel slag has been used on 19 major construction projects and further contracts continue to be served.

14.4 Using nickel slag in highway construction

Laboratory studies and increased use of ferrous and nonferrous slags in civil and highway construction have been conducted by researchers around the world (Shi, 2004; Wang & Montgomery, 1992; Farrand & Emery, 1995; Montgomery & Wang, 1993). Quantification work in laboratory evaluation of a specific slag is critical to ensure its appropriate use in highway construction (Wang, 2010).

Fig. 14.10 Crushing/screening river gravel to be blended with Falcondo aggregate for subbase and base material.

There are substantial environmental and economic benefits from using nickel slag in road construction. Because nickel slag is a molten coproduct of ferronickel production, its use in highway construction reduces the need to use natural materials, resulting in less exploitation of natural aggregate deposits. Use of nickel slag also reduces the need for its disposal and lowers the cost of producing new aggregate materials.

A laboratory evaluation of the use of AC nickel slag is conducted based on the nickel slag produced at the Falcondo facility in Bonao, Dominican Republic. Nickel slag is a coproduct of ferronickel production that is solidified under ambient atmospheric conditions. Laterite ore is open-pit mined and then processed through a preparation, reduction, and electric furnace melting process. Molten slag is removed from one end of the furnace and ferronickel is removed from the other end, for refining and shipment. The liquid nickel slag is transported by rail to a stockpile area where it is discharged and allowed to cool and solidify under ambient conditions. Then the solid slag is crushed, screened, and blended with river gravel for construction uses. (Fig. 8.3). This air-cooling results in some fragmentation into sizes conveniently suitable for riprap, armor stone, and gabion stone use. The fragmented AC nickel slag can be crushed and screened for a variety of construction aggregate purposes, as engineered fill, granular base and subbase, and HMA coarse and fine aggregate. Fig. 14.10 shows the aggregate processing site. Use of Falcondo aggregate significantly reduced the environmental impact of natural aggregates extraction and processing along the Autopista Duarte highway.

The purpose of this laboratory evaluation program was to fully assess the suitability of the nickel slag for use in construction and provide quantified data to support further potential use of AC nickel slag in highway construction. Slag aggregate sampling protocol was developed to assist field sampling that is included in Appendix IV.

14.4.1 Laboratory evaluation program

14.4.1.1 Materials

Two nickel slags, based on different cooling processes (ie, AC slag and emergency pit (EP) slag), were selected for this study. The laboratory work consisted of sample preparation, crushing and blending of large, bulk samples of AC nickel slag. Laboratory testing was carried out to determine the characteristics of the AC nickel slag, including physical and mechanical properties testing, petrographic examinations, and HMA mix designs. Accelerated laboratory testing was completed on the Marshall and Superpave HMA mixtures with the use of an APA to further assess their performance characteristics. Additional testing included autoclave disruption tests for free lime and free magnesia, chemical and mineralogical analyses, and determination of the PSV and AAV.

Experience and studies had indicated that the subject AC nickel slag was chemically stable and therefore had no leachate parameters of potential environmental concern when used in construction applications. As such, this evaluation program focused on the physical properties and mineral composition, with no supplementary environmental testing conducted.

Composite samples of AC slag and EP slag were obtained after they were crushed by using laboratory jaw crushers. The gradations of coarse and fine AC and EP slags after crushing are summarized in Table 14.15. The gradation analyses were carried out in accordance with the ASTM C136 test method for sieve analysis of fine and coarse aggregate.

14.4.1.2 Physical properties

The following physical properties tests were completed by using the composite samples of AC slag and EP slag: bulk relative density (BRD) and absorption testing of the coarse aggregate (retained 4.75 mm or No. 4 sieve) completed in accordance with the ASTM C127 test method, with the fine aggregate (passing 4.75 mm) tested

Table 14.15 **Gradations of nickel slag aggregate**

	Passing, % (coarse)		Passing, % (fine)	
Sieve size	**AC slag**	**EP slag**	**AC slag**	**EP slag**
1½ in. (37.5 mm)	100.0	100.0	–	–
1 in. (25.0 mm)	97.8	98.0	–	–
¾ in. (19 mm)	90.1	83.3	100	–
½ in. (12.5 mm)	66.2	52.9	97.1	–
⅜ in. (9.5 mm)	43.9	37.1	81.9	100
6.3 mm	25.8	24.3	*	*
No. 4 (4.75 mm)	19.3	19.6	37.0	98.7
No. 8 (2.36 mm)	10.3	11.8	18.4	71.4
No. 16 (1.18 mm)	6.3	7.7	10.6	50.6
No. 30 (600 µm)	4.1	5.2	6.9	38.3
No. 50 (300 µm)	2.8	3.4	4.7	29.3
No. 100 (150 µm)	1.9	2.1	3.2	21.7
No. 200 (75 µm)	1.3	1.1	2.3	14.6

Note: *, not required.

Table 14.16 Physical properties of nickel slag aggregate

Test		Test results (coarse)		Test results (fine)	
		AC slag	EP slag	AC slag	EP slag
BRD		3.157	3.192	3.182	3.306
Absorption (%)		1.11	1.00	1.25	0.73
Flat or elongated particles (%)	33:15	4.5	16.7	34.6	31.8
	44:1	1.1	9.5	22.8	19.8
	55:1	0.5	1.5	9.0	6.1
Unconfined freeze thaw (% loss)		0.8	0.2	49.8	48.3
Crushed content, one face (%)		100	100	98.2	89.0
Micro-Deval abrasion (% loss)		3.7	7.7	–	–
Los Angeles abrasion (% loss)		13.3	22.0	Not plastic	Not plastic
Magnesium sulphate soundness (% loss)		0.5	1.2	1.5	7.7
Sand equivalent		–	–	98	98

Note: –, not tested.

by using the ASTM C128 method; flat or elongated particles coarse aggregate testing, carried out in accordance with the ASTM D4791 test method (for both 3:1 and 5:1 aspect ratios); Micro-Deval abrasion testing in accordance with the Ministry of Transportation Ontario, Canada (MTO) LS-618 and LS-619 test procedures for coarse and fine aggregate, respectively; Los Angeles abrasion tests completed in accordance with ASTM C131 (using Grading B); and equivalent tests completed following the ASTM D2419 and AASHTO T176 test methods. Uncompacted voids tests were carried out in accordance with the AASHTO T304 procedure. Plasticity index testing was performed in accordance with the ASTM D4318 test method. Organic impurities testing of the fine aggregate were carried out in accordance with the ASTM C40 method.

Table 14.16 presents the physical properties of the coarse and fine AC nickel slag samples. It can be seen the BRD of slag is somewhat higher than that of natural aggregate. However, the BRD value itself did not affect the final binder content.

14.4.1.3 Chemical composition analysis

The chemical analysis results indicated that the chemical compositions of AC and EP slags were close. The subject cooling regimes had little influence on the chemical compositions of the two slags. The main chemical compositions of the slags were silicon dioxide (SiO_2), iron oxide (FeO), and magnesium oxide (MgO) (Table 14.17). The main mineral components of the AC and EP slags are ferromagnesium silicate minerals, which had the molecular composition $(Mg,Fe)2SiO_4$. It is the solid solution

Table 14.17 Chemical compositions of slag samples (%)

Sample	AC Slag	EP Slag
FeO	15.2	15.4
Fe_2O_3	5.8	5.3
SiO_2	50.2	50.5
MgO	26.7	26
CaO	1.8	2.2
f-CaO	<0.05	<0.05
Ni	0.16	0.17
MnO	0.35	0.36
P_2O_5	0.003	0.002
Na_2O	0.03	0.03
K_2O	0.03	0.03
Al_2O_3	<0.10	<0.10

Note: All numbers are percentages. Fe_2O_3, ferric oxides; *CaO*, calcium oxide (lime); *Ni*, nickel; *MnO*, manganese oxide; P_2O_5, diphosphorus pentoxide; Na_2O, disodium oxide; Al_2O_3, aluminum oxide.

of forsterite ($2MgO·SiO_2$) and fayalite ($2FeO·SiO_2$). No uncombined MgO monomers were observed in the AC or EP slag samples.

14.4.1.4 Scanning electron microscope analysis

A secondary imaging analysis method was used to observe FeO, SiO_2, MgO; back-reflection imaging was used for minerals that contained light metals, such as nickel, cobalt, and tungsten (Fig. 14.11). The results of the scanning electron microscope analysis showed that the minerals were mainly block and long-strip shaped.

14.4.1.5 Volumetric expansion testing

Volumetric expansion testing, carried out in accordance with the ASTM D4792 test method, indicated that the vertical volume expansion was 0.73% and 0.43% at 7 days for AC and EP slags, respectively. At these expansion values, both the AC and EP slag are well within the 2% limit typically specified for use in HMA applications.

14.4.1.6 PSV and AAV

PSV and AAV tests were carried out in accordance with the British Standards test method (BS 812) on samples of the AC and EP slags. The PSV is considered the most important aggregate characteristic that affects the frictional resistance of asphalt pavements. It provides an indication of the microtexture of the aggregate particles that represents a texture depth of less than 0.5 mm. The PSV is therefore a measure of the resistance of the surface of the aggregate particle to polishing under traffic. The AAV is used as a measure of the resistance of an aggregate to surface abrasion, or wear resistance, and is sometimes used to assess the suitability of an aggregate to provide pavement macrotexture. One AAV unit is considered to be equivalent to a difference of 0.05 mm in texture depth after 9 years of heavy traffic (Kechagia, 2004). The lower

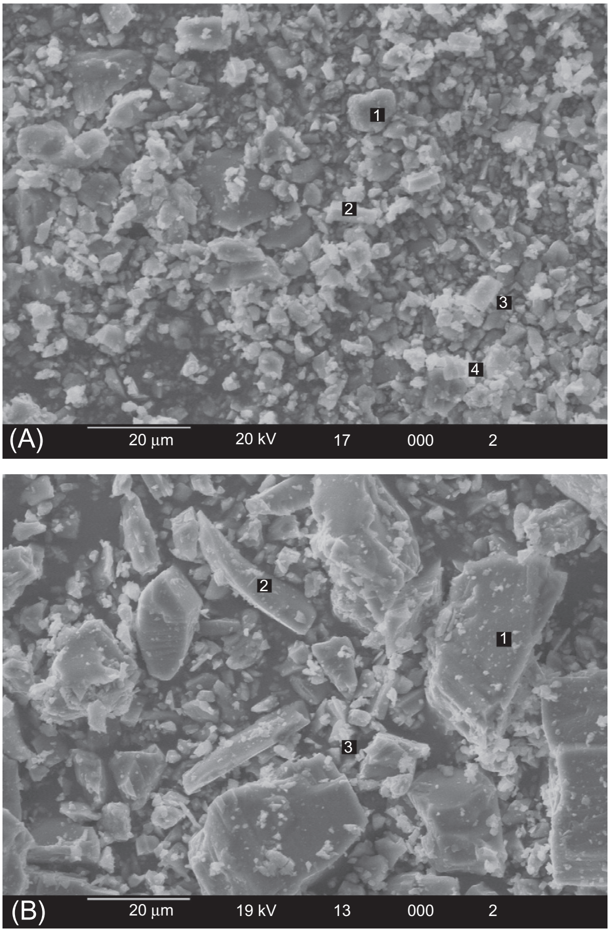

Fig. 14.11 Secondary imaging scan (×1000): (A) AC slag and (B) EP slag.

PSV test result for the current AC slag sample is likely indicative of the presence of flat, smooth particles (Table 14.18).

Natural limestone and dolostone aggregates (carbonates) typically exhibit PSV values ranging from about 31 to 44, which are used for surface course pavements. Clearly, the nickel slag exhibits frictional resistance values comparable to those specified for premium surface course aggregates.

Table 14.18 **Summary of PSV and AAV test results**

Sample	PSV	AAV
AC slag	47	1.8
EP slag	56	2.8

14.4.1.7 Petrographic examinations

Petrographic examinations were carried out in accordance with the procedure as described in ASTM C295–98: Guide for Petrographic Examination of Aggregates for Concrete. The results indicated that the coarse fractions (retained 4.75 mm) of AC slag and EP slags were hard and dense, with a very small amount of cemented fibers observed. The percentage of particles that can be scratched and peeled in EP slag was slightly higher than in AC slag.

The fine aggregate petrographic examination results indicated the presence of two types of nickel slag: (i) hard, crystalline particles whose individual crystals and minerals were readily distinguishable, bound together by either a microcrystalline or glassy and siliceous matrix and (ii) hard, microcrystalline particles that had a more massive appearance and individual grains and crystals could not be distinguished. The color of these particles ranged from black to white or clear, with occasional, relatively soft, reddish brown particles (possibly laterite ore). Both types of hard nickel slag particles were considered to be good (ie, could not be scratched, and individual grains or crystals could not be removed with a steel needle). Also observed were occasional vuggy nickel slag particles (that had obvious pores and vesicles; a few vugs were filled with soft, brown infilling). The brown infilling did not react with dilute hydrochloric acid. Although some brittle, white, fibrous-looking particles were observed in the coarse aggregate hand specimens, they were not readily apparent in the fine aggregate (these weaker coarse crystals most likely broke across their long axis during crushing into more regular, cubical shapes, and hence were not readily distinguishable).

14.4.1.8 Autoclave disruption testing

Autoclave disruption tests were carried out on the slag samples. The AC and EP slag samples were divided into four size fractions: pass 19.0 mm retained 16 mm; pass 16 mm retained 13.2 mm; pass 13.2 mm retained 9.5 mm; and pass 9.5 mm retained 4.75 mm. From visual examination, 50 particles of good, hard nickel slag were selected for each size fraction. These particles were then placed on a piece of filter paper on racks and suspended in a standard pressure cooker containing about 2 L of water. The pressure cooker was sealed and then the water was heated to boiling at 1 atmosphere pressure. The pressure was maintained for a period of 1 h, permitted to cool, and then the samples were removed. Each size fraction was carefully examined visually for signs of deterioration (e., cracking, disruption). Particles that did not exhibit any cracking or disruption were considered to be good; particles that were partially cracked were deemed fair; and particles that completely cracked, failed, or had softened were considered poor (Fig. 14.12).

The results (Tables 14.19 and 14.20) of the autoclave disruption testing indicate that the coarse nickel slag aggregate is generally suitable for use in HMA, consistently having autoclave disruption ratios of zero.

Fig. 14.12 presents the slag samples after autoclave testing, which proved nickel slag aggregates are hard, durable, and stable.

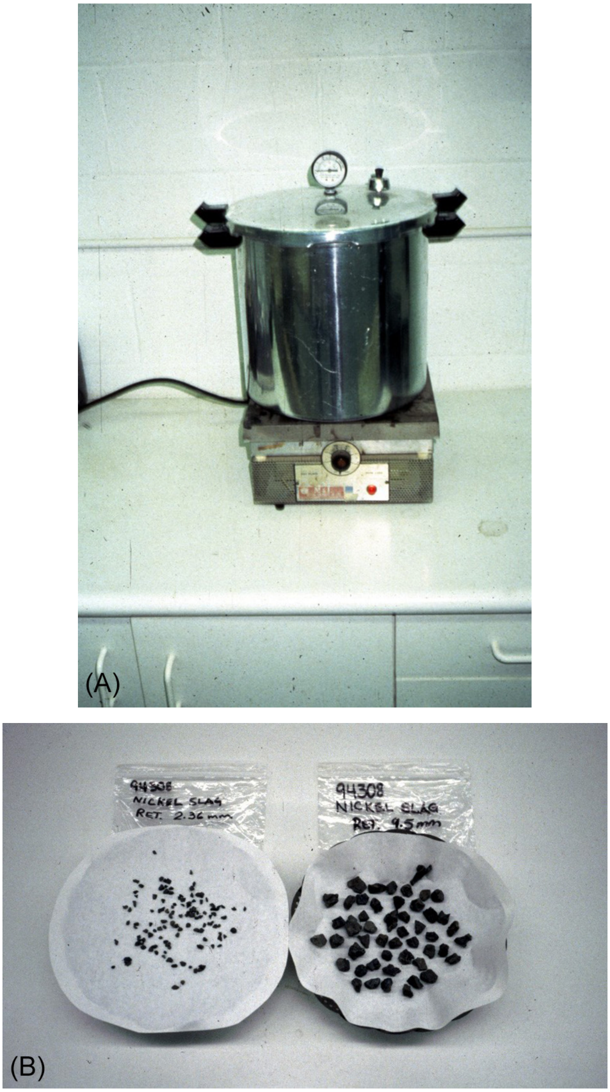

Fig. 14.12 (A) Autoclave test nickel slag aggregate and (B) aggregate after testing.

14.4.1.9 HMA mix designs

Heavy duty binder course (HDBC) (for traffic volume larger than 30×10^6 equivalent single axle loads) HMA mix designs were prepared for both AC and EP slags to assess and compare their suitability as coarse and fine aggregates in HMA. Mix designs were completed by using the conventional Marshall and Superpave volumetric methods.

Table 14.19 Autoclave disruption of AC slag

Size fraction (mm)		Total number of particles	Number of particles by quality after autoclaving			Disruption ratio (%)
			Good	Fair	Poor	
Sample 1	19.0–16.0	50	26	24		0
	16.0–13.2	50	33	17		0
	13.2–9.5	50	47	3		0
	9.5–4.75	50	45	5		0
	Average	50	38	12		0
Sample 2	19.0–16.0	50	30	20		0
	16.0–13.2	50	39	11		0
	13.2–9.5	50	43	7		0
	9.5–4.75	50	45	5		0
	Average	50	39	11		0
Test average		50	39	12		0

Table 14.20 Autoclave disruption of EP slag

Size fraction (mm)		Total number of particles	Number of particles by quality after autoclaving			Disruption ratio (%)
			Good	Fair	Poor	
Sample 1	19.0–16.0	50	49	1		0
	16.0–13.2	50	47	3		0
	13.2–9.5	50	47	3		0
	9.5–4.75	50	49	1		0
	Average	50	48	2		0
Sample 2	19.0–16.0	50	49	1		0
	16.0–13.2	50	49	1		0
	13.2–9.5	50	48	2		0
	9.5–4.75	50	47	3		0
	Average	50	48	2		0
Test average		50	48	2		0

The Marshall mix designs were carried out in accordance with the requirements given in the Asphalt Institute MS-2, *Mix Design Methods for Asphalt Concrete and Other Hot Mixes, Sixth Edition.*

The Superpave mix designs were completed in conformance with the Asphalt Institute Superpave Series No. 2 (SP-2). The Marshall mix design results (Tables 14.21 and 14.22) have been compared with the Asphalt Institute and with MTO specification requirements. As anticipated, the HDBC Marshall and Superpave (Table 14.23) mix designs for the AC and EP slag aggregates essentially confirmed

Table 14.21 HDBC mix design–job mix formula

Sieve size	Percent passing by dry mass		
	JMF		HDBC (MTO special provision)
	AC slag	EP slag	
26.5 mm	100.0	100.0	100
19.0 mm	98.5	98.5	94–100
16.0 mm	92.5	92.5	77–95
13.2 mm	86.0	86.0	65–90
9.5 mm	69.8	73.1	48–78
4.75 mm	46.6	46.6	–
2.36 mm	32.3	32.8	21–54
1.18 mm	21.8	21.4	12–49
600 µm	15.4	14.5	6–38
300 µm	10.2	9.3	3–22
150 µm	6.1	5.4	1–9
75 µm	3.1	3.1	0–6

Note: JMF, job mix formula.

Table 14.22 HDBC mix design: Marshall properties

Properties	Marshall properties		HDBC (OPSS/ MTO special provision)
	AC slag	EP slag	
Voids (%)	4.0	4.0	3.5–4.5
Flow, 0.25 mm	14.0	13.6	8 minimum
Stability (N)	16,691	17,354	8000 minimum
VMA (%)	14.5	15.7	14.0 minimum
Asphalt cement content (%)	5.2	5.3	4.7 minimum

Note: OPSS, Ontario Provincial Standard Specifications; *VMA*, voids in mineral aggregate.

Table 14.23 HDBC mix design summary Superpave properties (traffic $\geq 30 \times 10^6$ ESALs)

Superpave properties	Mix design data		Superpave requirement Asphalt Institute SP-2
	AC slag	EP slag	
Air void (%)	4.0	4.0	4.0
VMA (%)	14.0	15.2	13.0 (minimum)
Voids filled with asphalt (VFA, %)	71.5	73.7	65–75
Dust-to-binder ratio	0.9	0.8	0.6–1.2

the results obtained during the previous test (Lykoudis & Liapis, 2010; Montgomery & Wang, 1993; Nikolaidis, 2002).

The voids-in-the-mineral-aggregate difference between AC slag and EP slag was approximately 0.5%, which may have been the result of different cooling methods employed in the processing of the slag.

14.4.1.10 HMA rut resistance testing

HMA rut resistance testing was carried out by using an APA. The APA is a multi-functional, loaded wheel tester, which is used for accelerated performance testing of asphalt mixes. The APA features controllable wheel loads up to 113 kg (250 lb) and variable contact pressure. Pneumatic cylinders apply a repetitive load through a pressurized rubber hose to generate contact pressures up to 1378 kPa (200 psi) that are considered to be representative of actual field loading conditions. Calibration of the applied load, contact pressure, and deformation measurement is built into the APA system and is computer controlled. Triplicate beam samples or six cylindrical samples can be tested under controllable high temperatures and in dry or submerged (in water or other liquid) environments. Testing is completed in a microprocessor-controlled temperature chamber having a temperature range of 5–71°C (41–160°F). The Automated Data Acquisition System features software for measuring permanent deformation and fatigue and displays the results in both numerical and graphical format.

The HMA beams were tested under repetitive wheel loads for 8000 cycles. For this testing program, a higher pavement temperature of 64°C was selected to simulate the higher temperature environment to which paving mixtures in the Dominican Republic and southern United States. Most highway agencies using an APA would consider a 5 mm rut depth after 8000 cycles as the fail-pass criterion in designing asphalt concrete mixes for use on Interstate highways. The measured rut depths for the AC slag and EP slag HMA mixes were approximately 5.5 mm and 5.2 mm, respectively, which indicated that the HMA mixes prepared by using prototype laboratory processed aggregates exhibit good resistance to permanent deformation. The EP slag HDBC mix nearly meets the 5 mm deformation criteria for high-volume Interstate highways; the AC slag HDBC is also indicated to be good but for somewhat lower volume highways.

14.4.2 Using nickel slag in highway construction

One recent, positive use of large quantities of AC nickel slag occurred in the reconstruction and widening of the 140 km of the Dominican Republic's Duarte Highway from Santo Domingo (capital and largest city) north to Santiago (second largest city) at a cost of some US$150 million. This project was completed under the supervision of the Secretaria de Estado de Obras Públicas y Communicaciones (SEOPC) to the highest of international standards.

The SEOPC went to considerable efforts to mitigate the impact of the Duarte Highway construction work on the physical environment. The terrain, at several points along the route, required very deep and difficult cutting and filling, with extensive watercourse protection throughout and the use of large quantities of granular borrow fill. In addition to these borrow fill requirements (engineered fill), there was the requirement for large quantities of granular subbase and HMA crushed aggregates. The prime sources of these aggregates were large riverbed gravel deposits that were selected, processed, and rehabilitated to minimize environmental impacts. The SEOPC also implemented the use of nickel slag aggregate (stockpiled waste slag) as a large, environmentally friendly, suitable aggregate source from the Falconbridge Dominicana, S.A. laterite ore ferronickel smelter.

The Falcondo ferronickel smelter was conveniently located near the middle of the project with large quantities of nickel slag stockpiled in the slag disposal area. A thorough laboratory testing program was completed for the SEOPC to check the volume stability and leachate characteristics. Table 14.24 summarize s the testing results for nickel slag aggregates used in the construction of the Duarte Highway.

Table 14.24 Summary of test results of the nickel slag aggregates

	Sample		
Test	**Nominal 25 mm minus sample #1**	**Nominal 25 mm minus sample 2**	**Nominal retained 25 mm minus sample**
Autoclave disruption test (pass)			
1.18–2.36 mm	50/0/0 (good/fair/poor)	50/0/0	–
2.36–4.75 mm	50/0/0	49/1/0	–
4.75–6.7 mm	50/0/0	50/0/0	–
6.7–9.5 mm	50/0/0	50/0/0	–
9.5–13.2 mm	50/0/0	50/0/0	–
>25 mm	–	–	12/0/0
	Pass	Pass	Pass
Autoclave disruption testing was also completed for two particles of nickel slag that exhibited cracking attributed to thermal shock. Both particles passed the autoclave disruption test (remained sound and did not exhibit any additional cracking)			
Slag Aggregate Petrographic Examination Pass			
A 1700 g sample of the nominal 25 mm minus nickel slag (passing 25 mm retained 4.75 mm) was examined by a petrographer. The sample was found to consist solely of hard nickel slag. Occasional cracked particles were identified (thermal cracking) as well as some very vesicular particles, but no deleterious or nonslag particles were identified. One particle of nickel slag appeared to have some cemented sand attached to it, but the particle itself was hard			
Expansion test (pass)			
Percent expansion (7 days at 60°C)	0.06 (negligible)	0.04 (negligible)	Not tested

Note: –, not applicable.

Fig. 14.13 View of the nickel slag processing area near the construction site (A); and HMA mixing plant near the construction site (B).

Autoclave disruption was also completed for two particles of nickel slag, which exhibited cracking attributed to thermal shock. Both particles passed the autoclave test (remained sound and did not exhibit any additional cracking) (Fig. 4.12).

The nickel slag received full project approval for engineered fill, granular subbase, and HMA aggregate use based on practical, satisfactory local use for several years, and evaluations; and favorable comprehensive, accelerated stability, and durability testing. Several million cubic meters of the slag aggregates were used during the project, and thus replaced a substantial amount of river gravels, which made a positive contribution to the environment. Regular construction industry use of Falcondo aggregate is being established for domestic and export markets. Large quantities of nickel slag aggregate (some 10 million tonnes) were used for engineered fill, erosion protection stone, granular base material, and HMA aggregate during the reconstruction and widening of the Duarte Highway project. This resulted in further market development and a clear demonstration of technically sound, economical, and environmentally friendly use of Falcondo nickel slag aggregate. Fig. 14.13 shows the nickel slag processing site and HMA mixing facilities. Fig. 14.14 shows the paving site and the highway pavement surface condition in the 5th year after construction.

Fig. 14.14 Duarte Highway near Bonao, Dominican Republic: (A) Paving of HMA contains nickel slag aggregate (B) 5 years after construction.

14.4.3 Summary

The laboratory study and actual use of nickel slag indicated the strong potential suitability of the slag as HMA aggregate, as well as in granular base and subbase applications. Quantified laboratory evaluation and usability criteria are imperative for the full-scale use of various slags. To correctly use slags in highway construction and ensure the use is technically sound and durable, the following steps have to be followed: (i) select the right criterion for a specific use; (ii) conduct relevant laboratory testing to quantify the given sample; (iii) determine the usability on the basis of the relevant criterion; (iv) conduct field quality control; and (v) monitor long-term performance, which is the same as the use of normal, natural materials. Generally, the laboratory results confirmed the positive characteristics of AC nickel slag. The chemical and mineral composition of AC and EP slags are very similar. No significant differences in expansion were seen between untreated and autoclaved AC and EP slags. The APA performance tests indicate that measured rut depths for the AC slag and EP slag HMA mixes were similar that the HMA mixes prepared using prototype laboratory-processed aggregates, and they exhibited good resistance to permanent deformation.

Questions

14.1 Brief the testing procedures for the EAF slag used in Egnatia Odos, the 670 km highway project.

14.2 Describe stone column ground.

14.3 What types of testing were used for the EAF slag in stone column ground stabilization?

14.4 What types of testing were used to check the nickel slag used as granular materials and HMA aggregate.

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Comprehensive utilization of slag as system engineering: Challenges and opportunities

15

15.1 Introduction

The use or discovery of a new material and its use, in many cases, starts from instinctive, sometimes random activities, before a technical directive is developed in its initial stages, with little guidance. The use of slag is a similar situation. For example, slag used as road construction materials can be traced back to ancient history; slag use in cementitious applications attracted attention in the 18th century. During the Roman period, much slag was used for roadmaking, particularly in the region of the ironworks, and many such roads are uncovered in present-day excavations. For cementitious use, in 1728 John Payne patented a method for the use of blast furnace slag in England to make solid blocks. About 150 years later, in 1873 Charles Wood presented a paper to the Royal Society of Arts on the utilization of blast furnace slag to make blocks. In 1887, 75% of fine powdered and dried slag with 25% of dried slaked lime were used to produce slag cement (Lee, 1974). The first specification for slag cement appeared in 1902 by the Corps of Engineers, which covered puzzolan cement, made by "grinding together without subsequent calcination granulated blast furnace slag with slaked lime." After revisions, in ASTM Standard C219: Standard Terminology Relating to Hydraulic Cement, slag cement is defined as a "granulated blast furnace slag that has been ground to cement fineness, with or without additions, and that is a hydraulic cement." In the mid-2000s, copper and nickel slags were used with cements as pozzolanic materials. For blast furnace slag use as an aggregate, the earliest specifications were published in the mid-1900s in the United Kingdom and the United States. All these technical specifications are evolving and being improved, and new specifications are being developed through the current decade, even the definitions of slags.

Although the history of the use of slag is centuries old, the utilization rate is low in the world. This can come from any of the following inhibiting factors:

- Inherent variability
- Remote production locations
- Handling and processing costs
- Liability concerns for innovative technology
- User conservatism
- Obsolete specifications
- Inappropriate environmental constraints
- Industry pricing based on conventional materials
- Lack of technical guidance

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To eliminate these inhibitors, to transfer them to positive drivers for practical use, and to integrate efforts from all involved parties are the major tasks. These drivers or potential contributing factors include the areas of legislation and polices, standards and specifications, quality management, test methods and usability criteria, slag classification, education, and commercialization.

15.2 Contributing components in the integrated slag utilization system

Slags, including ferrous slags, have not to date received enough attention with regard to comprehensive utilization, except for ground granulated blast furnace slag (GGBFS), with low grade "use" or the accepted tradition being to be merely dumped as landfill. Over 200 million tonnes of slag were discharged in the world each year. In the United States, approximately 20 million tonnes of steel slag are produced each year, and hundreds of million tonnes of ferrous, nonferrous, and nonmetallurgical slags are generated. Any traditional disposal methods are environmentally and socially unacceptable and are not coordinative to the "three pillars of sustainability," in which both economy and society are constrained by environmental limits. Our society demands efficient and environmentally acceptable use of slag if it has been proven in practical applications. Proactively responding to growing environmental globalization concerns and natural resource shortages (both bulk and energy materials) is imperative for scientists and engineers to develop a wide range of environmentally acceptable, technically sound, and economically viable uses for slags and to transfer a slag from the "waste" stream, into a useful material "resource" stream.

In the broad sense, the comprehensive utilization of slag will have significant benefits in three major aspects. First, the use of slag in construction, which is the major industry that consumes mineral resources, will lead to a substantial reduction in environmental pollution due to reduced mining, processing, and firing, whereby the existing material is disposed of by landfilling and stockpiling. Second, the use of such material will supplement, or replace, the need for using natural mineral materials, thereby resulting in protection of natural, nonrenewable resources and a reduction in energy requirements associated with the winning of natural materials. Third, there exists the possibility of altering, improving, or modifying physical and chemical properties of conventional construction materials to produce special construction materials that can be utilized for specific applications.

To put slag into successful final use, the *use* has to be treated as system engineering and have policy makers, the slag industry, and final users involved.

15.2.1 Policies and regulations

In the use of slag (and other recycled materials), government agencies and owner organizations need to integrate the use of slag into an overall sustainability policy whereby formal guidance is put in place to require or encourage the use of slag, which includes coordinating various sectors and institutions; encouraging use of recycled by-product; and providing funding, information, or other needed resources to make the use of slag easier to achieve, all the while assisting in measuring the outcomes and evaluating its success.

Policies on the use of slag can come in the form of an executive order signed by a government agency leader, specifier, or a CEO of an organization; a bill passed by the legislature; or even an internal organizational directive issued by the executive staff.

15.2.1.1 European legislation

The activities of the European Slag Association (EUROSLAG) are closely related to the European legislation and the activities of the European Commission (EC). EUROSLAG has cooperated with EUROFER, the European Confederation of Iron and Steel Industries, especially with the Environment Committee and its subgroups to harmonize all activities and to stress that not only steel production but also slag production and use are important parameters for the continued existence of the European steel industry.

In some countries slag products are classified as wastes. In other countries certain slags are products and others are wastes. But currently no member of the EC has made a clear decision in favor of slags as products. Therefor, it is necessary to expedite the process of classifying, reclassifying, and subclassifying slag materials.

The European Waste Catalogue (EWC) established by the Commission Decision 2000/532/ECC of May 3, 2000, contains two entries regarding slags: (1) waste from the processing of slag and (2) unprocessed slag.

With regard to unprocessed slag it is important to stress that on a request from Germany, the EC agreed that granulation, palletization, foaming, proper solidification connected with a specified heat treatment and separation, crushing, sieving, and milling are examples of slag processing. This means that a slag that has undergone one or more of these processes is not covered by the EWC. These slags have no waste catalogue number. Thus, these slags should not be classified as wastes (Motz, 2005).

15.2.1.2 Registration, evaluation and authorization of chemicals

In Europe the Registration, Evaluation and Authorization of Chemicals (REACH) regulation was published in December 2006 and has been in force since January 1, 2007. Producers or importers of substances have not been allowed to place their substances on the market since before December 1, 2008, if they do not register them according to the REACH regulation. The registration of produced substances has started in the European steel industry (Bialucha, Motz, Sokol, & Kobesen, 2010; Hatscher, 2007).

In Germany, the FEhS-Institute (Research Institute for Iron and Steel Slags, Germany) together with EUROSLAG and the Working Committee of the REACH-Ferrous Slag-Consortium developed a procedure that allows for the successful registration of iron and steel slag within REACH. It is highlighted that the REACH registration actually reinforces the long-standing intention of the steel industry in Europe to produce and sell iron and steel slag as products or by-products but not as waste.

In the REACH registration, due to expertise and agreements with environmental authorities, some types of slag are established as by-products in Belgium, Finland, Germany, Austria, and the United Kingdom. In this context it refers to the decision of the EC from February 21, 2007, to accept blast furnace slag as by-product. On the other hand, iron and steel slags are registered as phase-in-substances. Accepting that slags are not wastes but products, an ad hoc working group "REACH" of the FEhS-Institute started the preregistration work on iron and steel slags in December 2006 aiming at a final registration before December 1, 2010.

Slags are grouped as monoconstituents substances, multiconstituent substances, or as UVCB substances (substances of unknown and variable composition, complex reaction products, or biological materials).

The REACH regulation is a change of responsibility: before the regulation entered into force the authorities had to identify critical substances and evaluate them. In the REACH system the responsibility for this process lies in the hands of the producers or importers of substances.

The REACH regulation distinguishes between manufacturers and users of substances. The users have to take care that their use is considered by the chemical safety report created by the registrant. The regulation demands an information exchange along the supply chain in both directions—upstream and downstream.

The steel industry is involved as a producer of iron and iron oxide, slag-like blast furnace slag, and basic oxygen furnace (BOF) and electric arc furnace (EAF) steel slag (Bialucha et al., 2010).

15.2.1.3 The United States

The United States has extensive and complex environmental laws that are designed to protect the public and the environment. The most important factor that ensures minimal risks to health and the environment from exposures to wastes and pollution is the degree of enforcement. In the United States there are both aggressive enforcement and major penalties for willful violations of environmental statutes. Even innocent violations or accidental releases of hazardous materials can result in very significant and costly fines. From a purely economic standpoint, private enterprises and governments cannot afford to be lax about the management of environmental issues surrounding their operations (Cheremisinoff, 2003).

The major US environmental laws are listed below.

- Clean Air Act (CAA)
- Clean Water Act (CWA)
- Emergency Planning and Community Right-To-Know Act (EPCRA)
- Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)
- National Environmental Policy Act (NEPA)
- Occupational Safety and Health Act (OSHA)
- Oil Pollution Act of 1990 (OPA)
- Pollution Prevention Act (PPA)
- Resource Conservation and Recovery Act (RCRA)
- Safe Drinking Water Act (SDWA)

- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund)
- Superfund Amendments and Reauthorization Act
- Toxic Substances Control Act (TSCA)

The laws directly related to by-products and solid wastes include NEPA, RCRA, PPA, TSCA.

15.2.1.4 National environmental policy act

The NEPA was passed in 1970 along with the Environmental Quality Improvement Act, the Environmental Education Act, and the Environmental Protection Agency (EPA). The main objective of these federal enactments was to ensure that the environment be protected against both public and private actions that failed to take account of costs or harms inflicted on the ecosystem. The EPA was supposed to monitor and analyze the environment, conduct research, and work closely with state and local governments to devise pollution control policies. NEPA has been described as some of the most far-reaching environmental legislation ever passed by Congress. The basic purpose of NEPA is to force governmental agencies to consider the effects on the environment of their decisions. State laws also reflect the same concerns, and common-law actions in nuisance allow adversely affected property owners to seek a judicial remedy for environmental harms.

15.2.1.5 Resource conservation and recovery act

RCRA is the Resource Conservation and Recovery Act, which was enacted by Congress in 1976. RCRA's primary goals are to protect human health and the environment from the potential hazards of waste disposal, to conserve energy and natural resources, to reduce the amount of waste generated, and to ensure that wastes are managed in an environmentally sound manner. RCRA regulates the management of solid waste (eg, garbage), hazardous waste, and underground storage tanks holding petroleum products or certain chemicals.

RCRA provides legal definitions of hazardous wastes. A waste may be considered hazardous if it is ignitable (ie, burns readily), corrosive, or reactive (eg, explosive). A waste may also be considered hazardous if it contains certain amounts of toxic chemicals. In addition to these characteristic wastes, EPA has also developed a list of more than 500 specific hazardous wastes.

In any given state, EPA or a state hazardous waste agency enforces the hazardous waste laws. EPA encourages states to assume primary responsibility for implementing the hazardous waste program through state adoption, authorization, and implementation of the regulations. Many types of businesses generate hazardous waste. According to the EPA regulations, solid waste means any garbage, or refuse, sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities (Cheremisinoff, 2003). In RCRA, iron and steel slag are excluded as a hazardous waste (Yzenas, 2011).

15.2.1.6 Pollution prevention act

The PPA focused industry, government, and public attention on reducing the amount of pollution through cost–effective changes in production, operation, and raw materials use. Opportunities for source reduction are often not realized because of existing regulations, and the industrial resources required for compliance, focus on treatment, and disposal. Source reduction is fundamentally different and more desirable than waste management or pollution control. Pollution prevention also includes other practices that increase efficiency in the use of energy, water, or other natural resources and protect our resource base through conservation. Practices include recycling, source reduction, and sustainable agriculture.

15.2.1.7 Toxic substances control act

The TSCA of 1976 was enacted by Congress to give EPA the ability to track the 75,000 industrial chemicals currently produced or imported into the United States.

15.2.1.8 Human Health Risk Assessment

In the United States, the Steel Slag Coalition (SSC), a group of 63 companies that produce steel, process slag, or both, has undertaken a comprehensive study of the chemical composition of three slag types generated during the steelmaking process and the potential human health and ecological risks associated with possible exposure to such slag. Based on new slag characterization data and the most current risk assessment guidance, including the new exposure models and toxicity information. As described herein, the current Human Health Risk Assessment (HHRA, 2011) confirmed the previous assessment finding that commercial and construction uses of steel industry slags do not pose a health risk (Yzenas, 2011).

15.2.2 Standards and specifications

Standards and specifications are very important guidance for correct use of slag in construction. They provide technical support that can be useful for creating capacity for sustainable construction and overcoming ignorance about new and innovative sustainable materials and techniques that may be different from the ways that things have typically been done. They provide guidance documents to distil the wide variety of available information on sustainability into a more concise format that contains information relevant for their specific context.

It is a collaborative task involving producers and users to develop and improve technical specifications. Good specifications promote the use of slag at the highest level and minimize any obstacles to the use of slag, promote the image of slag, and build confidence in members, products, and processes. EUROSLAG's experience is to form collaborative working groups to arrive at a uniform interpretation of European standardization and legislation. For example, the steam test method to evaluate the volume stability of steel slags and the categories declared by the aggregates standards of TC 154 are excellent examples of their successful cooperation in the past (Motz, 2005).

In developing specifications, the slag industry needs to have strong representation to get their interests accepted or observers or representatives to be sure that the standards discussed and drafted will respect slags as traditional aggregates.

The levels of standards and specifications on slag products and slag use are very different from country to country. For example, it is the practice in Ireland to add GGBFS in concrete mixes (I.S. EN 206-1: 2002, Concrete—Part 1: Specification, performance, production, and conformity). In Holland, a maximum 70–80% of GGBFS is allowed to be used in concrete. The levels of GGBFS permitted to be used with CEM I in Belgium is at 30% and 10% for different exposures in Belgium. In the United Kingdom, which has had an independent GGBFS industry for over 70 years, the norms permit a high level of GGBFS addition, up to 80%, to CEM I at the concrete mixes, for all exposure classes. Some other European countries have more restrictive rules governing the use of GGBFSS in concrete (CEN TC 104/WC104/WG15) (Seymour, 2007).

15.2.3 Quality control and quality management

Both producers and users need to develop their own quality control (QC), quality assurance (QA), and quality management system (QMS), and develop the necessary capabilities to meet the new material sampling, testing, and analysis requirements associated with related specifications, and without too much trauma. Users may have retesting and referee protocols available to deal with testing issues. The adoption of total quality management (TQM) or other QMS requires continuing producer–user interaction for effective, equitable implementation and monitoring to ensure that the statistical QA objectives are met. TQM can contribute to the overall performance of products containing slag.

TQM incorporates all of the activities associated with the continuous improvements of quality and productivity (service), with emphasis on customer–supplier relationships; employee involvement in decision making; teamwork; rigorous analysis of work as a process; statistical QC; and managerial focus on leading. The important TQM elements applicable to the use of slag in construction appear to be commitment and leadership; process emphasis; training; teamwork; fact-based decision making; involvement; and service.

A company whose business is based on the processing, development, and marketing of slag (or other by-products) is not in the same position, in all respects, as a company marketing traditional products. A prejudiced view is constantly taken of recycled products, which poses a big challenge to companies working in this sector. A company working in the by-products business must be able to show that both the technical and environmental properties of its products conform to the requirements of the authorities.

A certified integrated management system has proved to be a good tool for use in the QC and marketing of slag. Indeed the overall target of the management system is to guarantee that the customer's product or service is to their needs, produced in the best economic manner possible, and at the same time meets the requirements of both the authorities and the public at large.

QC is a challenge for the manufacturers of industrial products, especially when the same product can be used in a number of applications, so that it has to meet several standards simultaneously and be subjected to QC from different standpoints.

For many years, there had been minimal QC in the processing of slag and slag products production. The principal focus of the steelmakers or smelters was steel, and steel slag was treated as a by-product for disposal. The recent problems with SSA pavement and the resulting moratorium have forced the steel industry to change this view. In addition, rising costs and decreasing capacity at landfills have practically eliminated disposal as an option. The recent work has led to a proposed SSA specification and QC outline. A site-specific QC practice must be established at each source slag aggregate including the steelmaker and slag processor. The purpose of these controls is to ensure that an aggregate of suitable quality is produced for use in construction.

The new ISO 9001 standard promotes the adoption of a process approach when developing, implementing, and improving the effectiveness of a QMS, to enhance customer satisfaction by meeting customer requirements. Furthermore the standard mentions that for an organization to function effectively, it has to identify and manage numerous linked activities. An activity using resources, and managed to enable the transformation of inputs into outputs, can be considered as a process. Often the output from one process directly forms the input to the next. The application of a system of processes within an organization, together with the identification and interactions of these processes, and their management, can be referred to as the "process approach."

The same as other business, slag producers should consider every individual operation as a process, which starts from the customer and finishes with the customer. This chain of events starting and finishing with the customer contains numerous different stages, which are not even recognized in the organization. To recognize the existence of these multiple stage systems so-called operations diagrams have been prepared in many companies, the aims of which are to describe the different stages of only one process at a time. Regrettably, these fine diagrams often end up gathering dust in a file on a shelf; in other words they have not been put to any concrete use in the development of operations. Often, however, it is probable that there are grounds for drawing up of diagrams, when there is need to develop a certain process; the sales process, for example. It is reasonably easy to understand the overall picture with the aid of these diagrams and in this way to start development of the process by, for example, cutting out unnecessary stages. Quite often the unnecessary stages exist only because "things have always been done this way" and no one has ever stopped to think, "Is there a reason to change or develop operations?"

When used within a QMS the process approach emphasizes the importance of

- understanding and meeting requirements;
- the need to consider processes in terms of added value;

- obtaining results of process performance and effectiveness; and
- continual improvement of processes based on objective measurement.

In this new standard the continual development of processes is especially emphasized. As such, the continual improvement and development of operations is a precondition for any company wishing to retain its competitiveness. Continual improvement and development is, however, often carried out on the basis of thinking of how to cut costs; in practice, that is the cutting, directly in cash, of raw materials and other costs (Mäkikyrö, 2002).

15.2.4 Test methods and usability criteria development

It is imperative to develop new test methods and improve the existing ones. It is also necessary to establish usability criteria for various slag uses and combinations of materials. It is obsolete opinion to think that slag can only be co-used with virgin materials.

It must be realized that current specifications are generally behind the results from research and field trials.

The test method for slag characterization must target and be relevant to end use and the required end product properties.

Slag expansive property in a rigid matrix? Is it the same in an unbound matrix? How can an expansion test reflect these different behaviors in different matrices?

Another issue involves the blend use or co-use of slag with other by-products; processed tire rubber and recycled concrete aggregate, for example. What test methods can be developed for these blend uses? From the characteristics of the by-product(s), and the technical requirements of end products, what types of usability criteria can be established, which can be complicated, and combinations of both theoretic deductions and laboratory experiments.

15.2.5 Slag classification

15.2.5.1 The necessity

Standard organizations provide the definitions of slag; however, it is not enough to guide the use or identify or characterize a slag product, and sometimes one cannot give clear guidance in its use, as slag is a very general term. The same situation exists for other terms; for example, slag cement and slag aggregate.

For example, the American Society for Testing and Materials (ASTM) defines steel slag as a nonmetallic by-product, consisting of essentially calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium, and magnesium that is developed simultaneously with steel in basic oxygen, electric arc, or open-hearth furnaces. This is good; however, it is necessary to have detailed names, even labels to specify specific slag products. Classification and subclassification are needed. For example, EAF slag can be subclassified as carbon EAF slag (EAF C) and stainless steel EAF slag (EAF S) (Domas & Reynard, 2010).

It is a difficult task to determine the types, characteristics, and qualities of each major production process, and/or slag products, including detailed chemical and physical properties that provide information to users, and how to name them, and label them.

15.2.5.2 Classification and regulation

Only if we classify our products first, will the regulator, specifier, or decision maker be able to better classify them. It is fortunate we have a complete, consistent soil classification system; soil is not treated as a "dirt." When engineers see the name and label of a given soil, the properties and uses of the soil are reflected.

The European Waste Framework Directive (WFD) was published in November 2008. For the first time it excluded by-products from the scope of the directive. Additionally, a new article clarifies that waste materials may cease to be waste and can later on be seen as secondary raw materials.

For both points, the WFD gives some minimum criteria. The demands target lawful use for specific purposes and without any waste or typical further processing, an existing market (demand), and compliance with technical standards. It is presumed that the use of the substances will not lead to overall adverse environmental or human health impacts. The criteria will be worked out in more detail by use of a so-called comitology process, which involves the EC, Parliament, Council, and the EU member states, too. In front of this background, several parties have started to work out proposals and opinions to clarify the requirements on the substances. A first comitology process regarding end-of-waste (EoW) criteria for steel scrap was up and running in 2010 and will bring a material specific regulation. Additionally, it is clear that all substances that leave the waste regime will be part of product legislation such as the REACH directive. Supplementary challenges for authorities and industry result from the necessary implementation of the WFD while avoiding bureaucratic barriers.

BF slag is accepted as by-product. Acceptance of steel slag from BOF and EAF as by-product needs some more efforts. If BOF and EAF can be subclassified into categories, it may be easier to be accepted. It is also expected that there will be slag fractions that will not be able to fulfill by-product criteria, but may cease to be waste after some additional treatment. In these cases one should try to extent the comitology process on by-products to setting EoW criteria for these fractions, too. Regarding future chances, the steel industry hopes that the by-product status will result in a better image of slags as industrial minerals. Hopefully, this will be accompanied by better acceptance of the product slag and the production processes, which should have additional positive effects; for example, on approval procedures for steelworks installations. For trading it is expected that the by-product status will eliminate burden caused by waste law. It will ease shipment and improve market conditions. If it is not possible to become a by-product, it will not be possible to be accepted as high-quality material in the market. Finally, becoming a product may also be helpful in life cycle assessments on the steel industry's main product: steel.

On the other hand, the risks are not negligible. Acceptance as by-product for example is no guarantee for application, as there may be further legal regulations that may limit its use, such as the planned German regulation on alternative building materials. There is no doubt; comitology will leave some slag fractions in the waste regime. Additionally, it is yet to be seen that becoming a by-product may increase requirements for quality management, laboratory, handling, and so on, as long as present business does not comply with the future requirements of the by-product criteria. As all substances that are not part of the waste regime will be part of product legislation such as REACH, changes in products that are not covered by existing registration will initiate a new registration process. In front of these chances and in spite of the risks it is no question that time and effort are well invested in the case of by-product slag (Endemann, 2010).

Presently, notions such as by-product or secondary raw material have no legal relevance in the waste law of the European Union. Materials are simply waste or not. The European WFD is the basis for classification of materials as waste. According to this, waste is a substance or object the holder discards or intends or is required to discard. It is simply unacceptable that it is still under discussion whether metallurgical slag is a product or waste. It is necessary to clarify in what condition a substance is excluded from waste legislation as a product and when a waste ceases to be waste and becomes a secondary raw material such as steel scrap (Endemann, 2007).

The status of slags from the steel industry has been a much-debated issue during recent years. Is slag a product with valuable properties, sold to the customers to replace nonrenewable natural resources? Or is slag a waste created without a purpose and intended to be discarded—something for the environmental authorities to keep under close control?

In Europe, the definition of the concept of waste in the Directive on Waste is broad: materials that are discarded. In addition, a harmonized list on materials deemed waste has been published. The industry and the environmental authorities do not often see eye to eye on whether a material is considered waste or not. In recent years, interpretations of the concept of waste have been directed by the judgments and justifications of the EC Court of Justice. Both parties have tried to use parts of these judgments as arguments supporting their own points of view in the debate. Analysis of the decisions, made by the EC Court of Justice, shows that the concept of waste has been made significantly more extensive. The end result has often been irrational; classifying certain materials as waste has prevented the use of an industrial by-product and increased the use of nonrenewable natural resources. For example, classifying blast furnace slag as waste means that an environmental permit must be applied for separately for each site in earth and road construction, which already prevents the use of slag in most projects at the planning stage.

The EU Commission has also noticed problems and confusion in the interpretation of the concept of waste. The interpretation has been made broader by attorneys and solicitors, and this, in turn, hampers the recovery of materials, which replace natural resources as well as meeting the goals set for recycling. The EU Commission has expressed its intention to change the Directive on Waste in the near future to the required public notices. The application process currently lasts for a minimum of 3 months, which is far too long in the fast, modern pace of building work. Even knowing the fact that an environmental permit may be needed prevents engineers from considering slag as an alternative, even though it would be more financially sound and better in terms of technical qualities.

15.2.5.3 Definition of waste and interpretations of the EC Court of Justice

Is slag produced as a by-product of the steel industry or a waste? Slags have been used for tens of years with good results and they have their own loyal users. In Finland, defining slag as waste is based on an interpretation of the EU Directive on Waste and its position as a by-product of a primary production process.

The EU Directive on Waste (751442/ETY) defines waste as follows:

"Waste" shall mean any substance or object, which the holder discards or intends or is required to discard. In addition to the definition of waste, the European list of wastes (2000/532/EC) can be used to define whether a material is waste or not. Slags from the steel industry do not meet the definition of waste, because they have never been discarded from use. Instead, they are sold to consumers as products.

There are only two items in the European list of waste that refer to the slags from the steel industry: 10 02 01 "Wastes from the processing of slags" and 10 02 02 "Unprocessed slag." Slag products that will be sold do not apply to either of them. Of course, it must be remembered that the list is not complete and it also contains general "other wastes" groups, but using them to justify the definition of slag as waste is not sensible. Defining a material as waste must be based on the definition of waste itself and a holistic examination of the matter.

As far as blast furnace slag is concerned, all these questions can be answered positively. In this sense, considering slag a product is justified, too. In addition to hot metal, blast furnace slag is a product manufactured in the same process. The producers wish to produce slag and financially benefit from selling it to customers. Blast furnace products are strictly controlled, in compliance with the relevant standards, and no harm for the environment has been detected from their long-term use. Blast furnace slag, as any other product, can be considered waste only if no markets can be found for it due to economic reasons or local competition, or if it is left on a storage site for an indefinite period of time.

The definition of waste in compliance with the EC's legislation on waste has become significantly broader during recent years along with the judgments of the EC Court of Justice. The wide waste definition has made environmental authorities uncertain about the interpretation of the concept of waste. As a result, slags from the steel industry that have been used for a long time to replace natural resources have been classified as waste. This is justified by appealing to the legislative definition of waste. Other justifications related to the protection of the environment have not been stated. Classifying slags from the steel industry as waste would significantly hamper their use. This, in turn, would increase the use of natural resources, which cannot be considered a sensible solution for the environment.

In Europe, the stricter, unclear interpretation of waste made by the EC Court of Justice has caused problems also for recycled products manufactured from waste. Products that are ready for use are now considered waste until they have been turned into end products in the recovery process. Labeling recycled products as waste hampers and partly prevents their recovery. The EU Commission has stated that it will make an initiative on changing the Directive on Waste in such a way that problems arising in the interpretation of the definition of waste can be eliminated. Essential questions for the steel industry will be the creation of a definition for by-products of industrial processes. By-products cannot be automatically defined as waste, if they are genuinely commercial products that meet the needs of the customers and the environment. On the other hand, it is necessary to make a slag product or waste—the present situation difference between secondary product and products produced from waste and a separate name for them must be found; for example, secondary product or raw material. Blast furnace slag, a by-product of the steel industry, is a good example of a by-product that is not waste at any stage but meets the characteristics of a product and is sold to customers.

According to the EU legislation on waste, it is preferable to promote the use of industrial by-products and recycled products made of wastes, which can replace natural resources. It is much preferred that the future change in the directive on waste will promote this by clarifying and harmonizing the somewhat confused definition of the word “waste” (Haimi, 2005).

15.2.6 Education and training

Education and training are important to allow students and professionals to expose to and understand slag, as a nontraditional material can make positive contributions to various end products of construction that conventional materials may not make. Education most likely happens in classrooms, from textbooks, and instructors. The objects of training can be users, producers, or educators who educate future users to use slag in their projects.

15.2.6.1 Education

Most current textbooks for undergraduate programs in construction engineering, civil engineering, or construction materials do not cover detailed slag utilizations. This needs to be rectified. An effective way to fill this gap is to do micro insertion to standalone courses; that is, “insert” slag utilization chapters into certain courses, such as infrastructure construction, construction materials, highway materials, concrete technology, asphalt paving, hot-mix asphalt materials, and geomaterials. Most of the instruction will be conducted by university faculty members. It is also important to have experts from the industry deliver lectures on slag utilization and visit nearby producers or projects. Fig. 15.1 shows Nucor Corporation presenting sustainability principles to students, researchers, and faculty of East Carolina University.

15.2.6.2 Training

The object of training is broad. Unlike education of college and university students, technical training can be very flexible in terms of timing, contents, background, and prerequisites. Training opportunities can also be used to inform professionals, stakeholders, and managerial personnel on topics ranging from general sustainability, sustainable construction principles, sustainable material, rating system requirements, government regulations on slag, recent development of slag use and research, or technical details of specific technologies. Organizations may not need to implement training internally but instead may find ways to increase the number of personnel attending existing training events such as subsidizing the cost of training, providing release time to attend, or

Fig. 15.1 Engineers from Nucor Corporation explaining the imperatives of sustainable development of the society to students, scientists, and faculty.

merely encouraging attendance at training seminars. Creating programs of awareness, and awards for slag studies should also be included in a training program.

15.2.7 Commercialization

15.2.7.1 Education

Education is a long-term investment and a commercialization strategy. Education in civil engineering, consecution engineering, civil engineering technology, and construction management can be a long-term strategic commercialization of slag. Continuous industry or association outreach to colleges and university, and forming partnerships or acting as advisory members are part of this outreach.

15.2.7.2 Projects demonstration

Demonstration of a previous project or pilot projects can show potential users the benefits in the context of a real project by using slag products, the constitution techniques, and long-term performance. A successful pilot project can help dispel the fears and objections of opponents, and incurs a much lower political cost and risk than formally putting a policy into place.

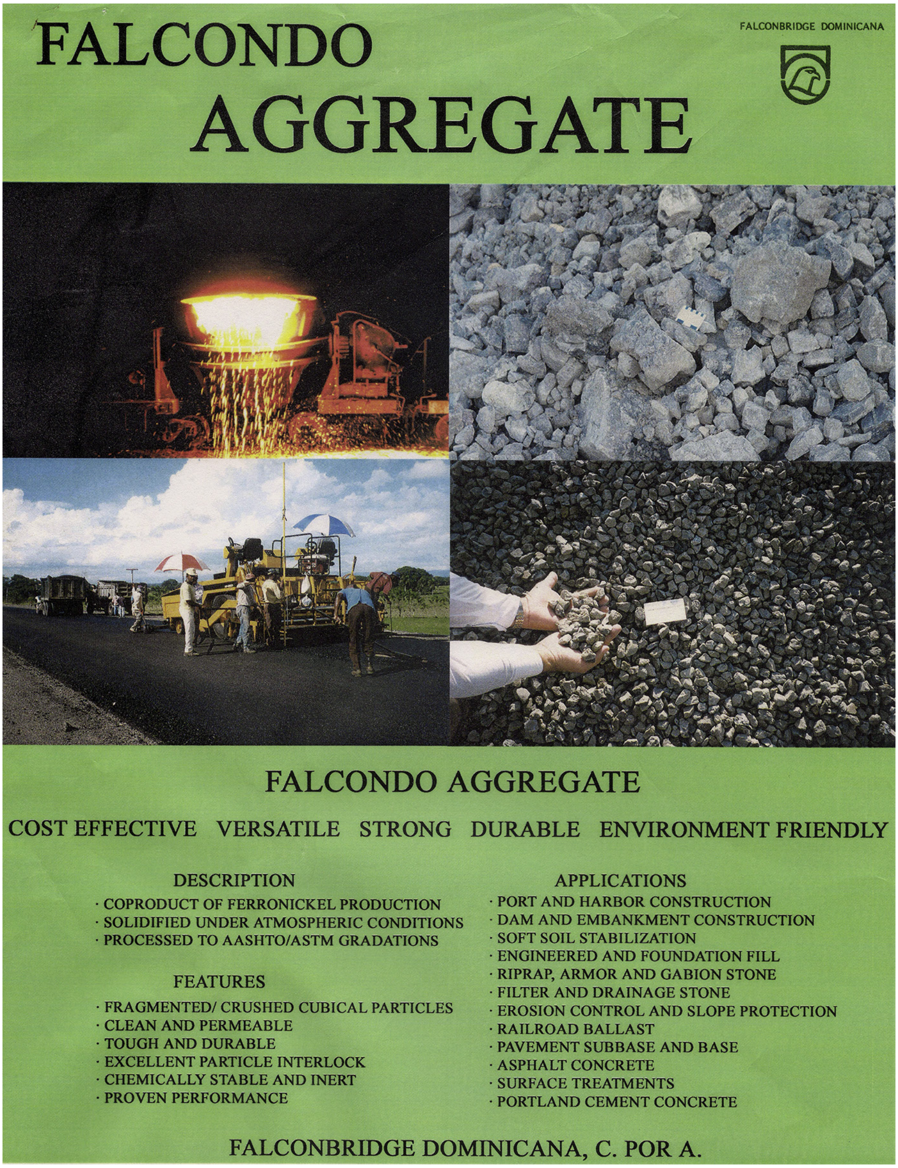
The demonstration does not exclude inviting potential users, including college and university students, to the facilities of slag process and production and laboratories to monitor the processes of production, QC and QA in production sites and the laboratory.

15.2.7.3 Incentives and subsidies

Another approach is to reward a contractor that is "ahead of the curve" in already pursuing the practices of using slag and provide motivation for other contractors to follow the lead. Incentives observed in some organizations, for instance, include reimbursing the cost of rating system certification, leadership awards for new projects, improved performance reviews for involved individuals, and positive press coverage.

15.2.7.4 Marketing slag product

Giving a slag product a proper commercial product name is important. The product name of a mature slag product does not have to include the term "slag." This is because the term slag may be too generic for a specific product and may cause confusion. Its origination can be illustrated in the product information sheet. Fig. 15.2 is a cover of brochure for nickel slag aggregate produced in Falconbride Dominican Republic. The nickel slag aggregate is given a commercial name, Falcondo Aggregate.



FALCONDO
AGGREGATE

FALCONBRIDGE DOMINICANA

FALCONDO AGGREGATE

COST EFFECTIVE VERSATILE STRONG DURABLE ENVIRONMENT FRIENDLY

DESCRIPTION
- COPRODUCT OF FERRONICKEL PRODUCTION
- SOLIDIFIED UNDER ATMOSPHERIC CONDITIONS
- PROCESSED TO AASHTO/ASTM GRADATIONS

FEATURES
- FRAGMENTED/ CRUSHED CUBICAL PARTICLES
- CLEAN AND PERMEABLE
- TOUGH AND DURABLE
- EXCELLENT PARTICLE INTERLOCK
- CHEMICALLY STABLE AND INERT
- PROVEN PERFORMANCE

APPLICATIONS
- PORT AND HARBOR CONSTRUCTION
- DAM AND EMBANKMENT CONSTRUCTION
- SOFT SOIL STABILIZATION
- ENGINEERED AND FOUNDATION FILL
- RIPRAP, ARMOR AND GABION STONE
- FILTER AND DRAINAGE STONE
- EROSION CONTROL AND SLOPE PROTECTION
- RAILROAD BALLAST
- PAVEMENT SUBBASE AND BASE
- ASPHALT CONCRETE
- SURFACE TREATMENTS
- PORTLAND CEMENT CONCRETE

FALCONBRIDGE DOMINICANA, C. POR A.

Fig. 15.2 Falcondo Aggregate product brochure (cover page).

15.3 Compilation of slag specifications

A compilation of standard test methods and specializations that related to slag, conventional materials, and end products containing slag is presented in this section.

15.3.1 Standard test methods and specifications for slag and end products containing slag

Table 15.1 provides the standard test methods and specifications for slag and end products containing slag, which are mainly from ASTM, AASHTO, and EN standards.

15.3.2 Slag uses

Table 15.2 provides the standard test methods and specifications for conventional materials, which may be used to examine slag materials, which are mainly from ASTM, AASHTO, and EN standards.

Table 15.1 **Standard test methods and specifications for slag and end products containing slag**

Number	Title
ASTM C989/C989M-14	Standard specification for slag cement for use in concrete and mortars
ASTM D5106-15	Standard specification for steel slag aggregates for bituminous paving mixtures
ASTM D6155-15	Standard specification for nontraditional coarse aggregates for bituminous paving mixtures
ASTM C595	Standard specification for blended hydraulic cements
ASTM C1308	Accelerated leach test for diffusive releases from solidified waste and a computer program to model diffusive, fractional leaching from cylindrical waste forms
ASTM D4874-14	Leaching solid material in a column apparatus
BS 1047:1983	Specification for air-cooled blast furnace slag aggregate for use in construction
BS EN 933-1:2012	Geometrical properties of aggregates. Determination of particle size distribution. Sieving method
BS EN 1097-6:2013	Mechanical and physical properties of aggregates. Determination of particle density and water absorption
BS EN 1744-1:2009 + A1:2012	Chemical properties of aggregates. Chemical analysis
BS EN 1097-3:1998	Mechanical and physical properties of aggregates. Determination of loose bulk density and voids
BS EN 12457-3:2002	Characterization of waste. Leaching
BS EN 13043:2002	Aggregates for bituminous mixtures and surface treatments for roads, airfields, and other trafficked areas
BS EN 13242:2002 + A1:2007	Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction
BS EN 13657:2002	Characterization of waste. Digestion for subsequent determination of aqua regia soluble portion of elements

Table 15.2 Specifications for conventional materials that can be used for the end products containing slag

Number	Title
ASTM D4215	Cold-mixed, cold-laid bituminous paving mixtures
ASTM D3987-12	Shake extraction of solid waste with water
ASTM C114-00	Chemical analysis of hydraulic cement
ASTM C125-15b	Standard terminology relating to concrete and concrete aggregates
ASTM D4792/D4792M-13	Standard test method for aggregates from hydration reactions
ASTM D448-12	Standard classification for sizes of aggregates for road and bridge construction
ASTM C131/C131M-14	Resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine
ASTM C535-12	Resistance to degradation of large-size coarse aggregate by abrasion and impact in the Los Angeles machine
ASTM D7428-15	Resistance of fine aggregate to degradation by abrasion in the Micro-Deval apparatus
ASTM D6928-10	Resistance of coarse aggregate to degradation by abrasion in the Micro-Deval apparatus
ASTM C88-13	Soundness of aggregates by use of sodium sulfate or magnesium sulfate
ASTM C127-15	Relative density (specific gravity) and absorption of coarse aggregate
ASTM C131/C131M-14	Resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine
ASTM C142/C142M-10	Clay lumps and friable particles in aggregates
ASTM C666/C666M-15	Resistance of concrete to rapid freezing and thawing
ASTM C215-14	Fundamental transverse, longitudinal, and torsional resonant frequencies of concrete specimens
ASTM C192/C192M-15	Making and curing concrete test specimens in the laboratory
ASTM C597-09	Pulse velocity through concrete
ASTM C123/C123M-14	Lightweight particles in aggregate
ASTM C117-13	Materials finer than 75 μm (No. 200) sieve in mineral aggregates by washing
ASTM C33/C33M-13	Standard specification for concrete aggregates
ASTM C40/C40M-11	Organic impurities in fine aggregates for concrete
ASTM C227-10	Potential alkali reactivity of cement-aggregate combinations (mortar-bar method)
ASTM D1308-02(2013)	Effect of household chemicals on clear and pigmented organic finishes
ASTM D2419-14	Sand equivalent value of soils and fine aggregate
ASTM C131/C131M-14	Resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine
ASTM C535-12	Resistance to degradation of large-size coarse aggregate by abrasion and impact in the Los Angeles machine
ASTM E274/E274M-15	Skid resistance of paved surfaces using a full-scale tire
ASTM D4791-10	Flat particles, elongated particles, or flat and elongated particles in coarse aggregate

(Continued)

Table 15.2 Specifications for conventional materials that can be used for the end products containing slag—Cont'd

Number	Title
ASTM D6084/D6084M-13	Elastic recovery of bituminous materials by ductilometer
ASTM D4402/D4402M-15	Viscosity determination of asphalt at elevated temperatures using a rotational viscometer
AASHTO M57-80 (2012)	Materials for embankments and subgrades
AASHTO M145-91 (2012)	Classification of soils and soil-aggregate mixtures for highway construction purposes
AASHTO M146-91 (2012)	Terms relating to subgrade, soil-aggregate, and fill materials
AASHTO M147-65 (2012)	Materials for aggregate and soil-aggregate subbase, base, and surface courses
AASHTO M80-13	Coarse aggregate for hydraulic cement concrete
AASHTO T176 (2008)	Plastic fines in graded aggregates and soils by use of the sand equivalent test
AASHTO T96	Resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine
AASHTO T85-14	Specific gravity and absorption of coarse aggregate (ASTM C127-12)
AASHTO T48-1996	Flash and fire points by Cleveland open cup ASTM D92-90
AASHTO T176	Plastic fines in graded aggregates and soils by use of the sand equivalent test
AASHTO T49-15	Penetration of bituminous materials (ASTM D 5/D5M-13)
AASHTO T23-14	Making and curing concrete test specimens in the field (ASTM C31-06)
AASHTO T84-00 (2004)	Specific gravity and absorption of fine aggregate (ASTM C 128-97)
AASHTO T53-09 (2013)	Softening point of bitumen (ring-and-ball apparatus), (ASTM D36-06)
AASHTO T104 (2003)	Soundness of aggregate by use of sodium sulfate or magnesium sulfate
AASHTO T51-09 (2013)	Ductility of asphalt materials (ASTM D113-07)
EN12593	Bitumen and bituminous binders — determination of the Fraass breaking point
BS EN1744-3:2002	Chemical properties of aggregates. Preparation of eluates by leaching of aggregates
BS EN 1744-1:2009+A1:2012	Chemical properties of aggregates
BS EN12457-2:2002	Characterization of waste. Leaching
BS812-113:1990	Testing aggregates. Method for determination of aggregate abrasion value
BS 812-105.1:1989	Testing aggregates. Methods for determination of particle shape. Flakiness index
BS EN197-1:2011	Cement. Composition, specifications, and conformity criteria for common cements (British standard)
BS EN933	Tests for geometrical properties of aggregates
BS EN1097	Tests for mechanical and physical properties of aggregates

Table 15.2 **Specifications for conventional materials that can be used for the end products containing slag—Cont'd**

Number	Title
BS 1047:1983	Air-cooled blast furnace slag aggregate for use in construction
BS 812-103.1:1985	Method for determination of particle size distribution. Sieve tests
BS EN 13242:2002+A1:2007	Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction
BS EN13285:2010	Unbound mixtures. Specifications
BS EN14227-2:2013	Hydraulically bound mixtures. Specifications. Slag bound granular mixtures
BS EN13383-2:2013	Armourstone. Test methods
BS EN197-1:2000	Cement. Composition, specifications, and conformity criteria for common cements
BS EN206:2013	Concrete. Specification, performance, production, and conformity
BS 4987-1:2005	Coated macadam (asphalt concrete) for roads and other paved areas. Specification for constituent materials and for mixtures
CEN TC 154/SC 2 N 253	Aggregates for concrete including those for use in roads and pavements
CEN TC 292	Characterization of waste

15.4 Summary

The limited use of slag in construction could come from two sides: the technical side and/or the managerial and the legislative side.

Future efforts should be placed on multiple levels and have all stakeholders involved in every step of the implementation of the use of slag.

A conservative view of slag or discrimination of by-products, nonconventional materials, and products made of these materials and making comparison to products made of virgin materials are not acceptable and contrary to the aim of sustainable management. The use of by-products, nonconventional materials, recycled materials, and secondary materials must receive first priority. It would be a shame if factors such as specifier conservatism or lack of technical guidance continue to limit slag use in civil infrastructure construction by some agencies when it is clear that a specific use is technologically sound and environmentally favorable and that it contributes to sustainable development of our society.

Questions

15.1 List the inhibiting factors in slag utilization.
15.2 What are the significant benefits of slag utilization.
15.3 List potential contributing components in slag utilization.
15.4 Which US laws are directly related to by-products or solid wastes?
15.5 How QC and QA can be used in slag product production?

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Appendix 1: Procedures to determine disruption ratio of expansive slag

This method was initially developed and used by the author in the deduction of single slag particle expansion force from a bulk slag sample. The method has been modified and adopted in testing basic oxygen furnace, electric arc furnace, and nickel slag aggregate samples, as indicated in the text. The test method is necessary in the usability deduction for slag use in rigid matrices. How to use the results is presented in Chapters 12 and 14.

Determination of particle cracking ratio (for coarse and fine slag aggregates)

1. Scope of method
   This test method covers the determination of percentage of unstable particles in steel slag aggregate that contain higher components susceptible to hydration and consequent volume increase, such as free calcium and magnesium oxides. This method can be used for other ferrous, nonferrous, and nonmetallurgical slags to check the volumetric stability.
2. Summary of test method
   This test method consists of measuring the content of unstable steel slag aggregate particles that are likely to crack or powder. When the contents of free calcium and/or magnesium oxides are higher than a certain limit in steel slag aggregates, it is necessary for these steel slag aggregates to pass the particle disruption ratio test before being put into use. To accelerate the hydration reaction, steel slag aggregate particles are tested in an autoclave or pressure cooker, for example, at 112°C (10 N/cm^2 or 14 psi).
3. Significance and use
   - **3.1** This test method provides a procedure for determining steel slag aggregates with specifications or special requirements, such as requirements for steel slag aggregates in asphaltic concrete, which limit permissible contents of free calcium and magnesium oxides subject to hydration; steel slag in a rigid matrix as a coarse aggregate.
   - **3.2** This test method can also be used to evaluate the effectiveness of aging or other treatment for reducing the expansive potential of steel slag aggregates.
   - **3.3** Test results have been correlated with a usability criterion for use of steel slag aggregate in rigid matrices such as Portland cement matrix or asphalt cement matrix under low temperatures. Particle disruption ratio is one of the important factors for evaluating the usability of steel slag aggregate.
   - **3.4** The method can be extended to other slags that are prone to volumetric expansion.
4. Apparatus
   - **4.1** Metal brush, tray, ruler, tap water.
   - **4.2** Autoclave or pressure cooker (Fig. A1.1), controlled at 10 N/m^2 or 14 psi pressure (at ~ 112°C).

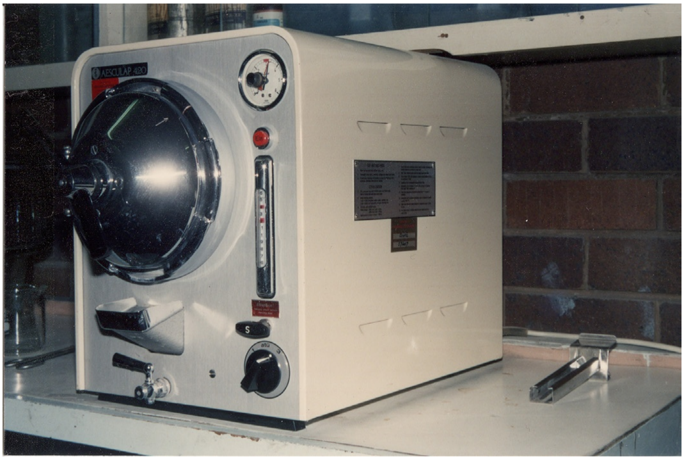

Fig. A1.1 An autoclave for disruption ratio test.

5. Sampling
   - **5.1** Take 10 kg field samples in accordance with requirements of steel slag aggregates.
   - **5.2** For coarse aggregate, 200 steel slag particles shall be chosen from a 10 kg coarse steel slag aggregate sample of the same nominal particle size.
   - **5.3** For fine aggregate, 200 steel slag particles of 4.75 mm particle size shall be chosen from a 10 kg fine steel slag aggregate sample.
   - **5.4** No harmful particles (visible to the naked eye) are allowed in the 200 particle sample.
6. Preparation of sample
   - **6.1** Wash the particles one by one using tap water and a hard metal brush, discarding soft, powdered, cracked particles. Clean the whole surface of steel slag particles and ensure no white coating nor white embedded matter on the surface.
   - **6.2** 150 particles shall be chosen and be divided into 3 groups, 50 particles in each group set aside for the test.
7. Test and calculation
   - **7.1** Put 50 particles in an autoclave or pressure cooker. Keep sufficient water in the autoclave during the test. Treat for 60 minutes, at a constant pressure, excluding pressure rise and decrease periods. Pressure shall be kept at 10 N/cm^2 or 14 psi.
   - **7.2** Take out after cooling down and determine the number of unstable particles. Particles totally powdered or cracked shall be treated as unstable. Powdered particle with a total diameter of powdered matter less than one-tenth of the nominal particle size of the sample, should be treated as stable particle. Cracked particle with a total thickness of cracked portion less than one-tenth of the nominal particle size of the sample should be treated as stable particle.
   - **7.3** Repeat 7.1 and 7.2 twice for the other two groups of steel slag aggregate samples.
   - **7.4** Calculate the particle disruption ratio following 7.1 and 7.2 from the formula

$$R = N_U / N_T \times 100\%$$

where R is the particle cracking ratio (%); N_U is the number of unstable steel slag aggregate particles; and N_T is the number of total steel slag aggregate particles for each test.

Take the average of three results for the particle cracking ratio value.

Appendix 2: Procedures to determine metallic iron content in steel slag

The following was adopted by the author in research to determine metallic iron content in steel slag.

Determination of metallic iron content in steel slag

1. Reagents and chemicals
   - **a.** 10% Copper sulfate ($CuSO_4$);
   - **b.** 1:1 Sulfuric acid (H_2SO_4);
   - **c.** Strong phosphoric acid (H_3PO_4);
   - **d.** 0.1 N potassium dichromate ($K_2Cr_2O_7$s volumetric standard);
   - **e.** 1% bromocresol indicator;
   - **f.** Metallic aluminum (foil, 0.5 mm thick).
2. Procedure
   - **a.** Weigh about one gram sample passing 0.075 mm sieve, put the sample into a 400 ml beaker;
   - **b.** Add 20–25 ml 10% copper sulfate solution and dilute with 20–25 ml hot water. Boil for 15 minutes and add water to keep 50 ml volume totally;
   - **c.** Filter and wash with hot water and dilute to 100 ml. Add 14 ml 1:1 sulfuric acid and a piece of metallic aluminum;
   - **d.** Keep boiling until all copper settles, then cool, filter, and wash with cool water, dilute to 250 ml. Add 3 drops of bromocresol indicator and 5 ml strong phosphoric acid. Titrate using 0.1 N potassium dichromate until purple color occurs.
3. Calculation of metallic iron content in steel slag

$$\mathrm{Fe\%} = N \times V \times 0.05585 \times 100G$$

where

N = Potassium dichromate standard solution;

V = Volume of potassium dichromate consumed for titration (ml);

G = Weight of sample (g); 0.05585 = Weight (g) of metallic iron per mg equivalence.

Appendix 3: Procedures to determine free calcium oxide content in steel slag

Presented below is one of the methods the author adopted to determine the free CaO in BOF slag, which includes two steps. The first step is to determine the total calcium (CaO) content, while the second step is to determine the calcium hydroxide ($Ca(OH)_2$) content. The difference of the two values will be the free CaO content in slag samples. The main reason for the second step is that slag samples, in most cases, have undergone some extent of hydration, including free CaO.

A3.1 Step 1 Total calcium content (benzoic titration method)

A3.1.1 Preparation of reagents

(i) *Absolute alcohol (water-free alcohol)*: fresh burnt lime is to be put into 99.5% commercial chemical alcohol ($C_2H_5OH = 46.07$, ethanol 99.7% to 100% v/v) for one night, or 12 hours, and the alcohol is to be distilled at 78–79 °C. The distilled alcohol will be stored in a dry bottle.

(ii) *Strontium nitrate* (solid, anhydrous, $Sr\,(NO_3)_2 = 211.63$) is to be used as a catalyst.

(iii) *Glycerol*: Chemically pure glycerol ($CH_2OH{\cdot}CHOH{\cdot}CH_2OH = 92.09$) is to be poured into a dry beaker and heated on a hot plate at 160–170 °C for 3 hours to make water evaporate (temperature is measured when heating).

The titration of benzoic acid standard solution with CaO:

$$\mathrm{TCaO} = \frac{a}{v} \tag{A3.1}$$

where,

TCaO = equivalent mass (in grams) of CaO in 1 ml benzoic acid standard solution;
a = weight of CaO (g) used;
v = volume of benzoic acid consumed for titrating (mL).

A3.1.2 Preparation of slag sample

A minus 75 μm sample is to be used for the test. Materials should be ground and sieved. Slag containing f-CaO, having this degree of fineness, is considered to be dissolved completely in glycerol solution during the test, through repeated boiling and titrating until final boiling for 20 min., results in the pink color not occurring any more (no more CaO comes out).

A3.1.3 Titration: benzoic acid standard solution

Exactly weigh out a 0.2 – 0.5 g sample, put it into a 150 ml dried Erlenmeyer flask, put a 15 ml solution of glycerin and alcohol into the flask and shake to disperse. Connect the condenser and heat the flask on a hot plate, and boil for 10 min. Take it off the heat when the liquid becomes red, and immediately titrate using benzoic standard solution until the red color disappears, and then connect it with the condenser again. Repeat this procedure until the final heating for 20 min results in no red color occurring. Fig. A3.1 shows the test.

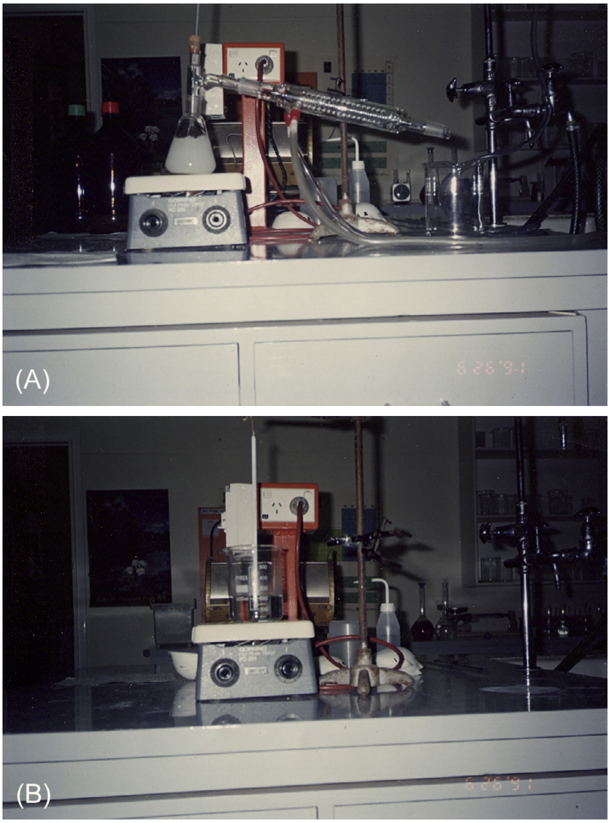

Fig. A3.1 Testing total CaO content by using benzoic titration method. (A) distilling of ethanol; (B) purification of glycerol

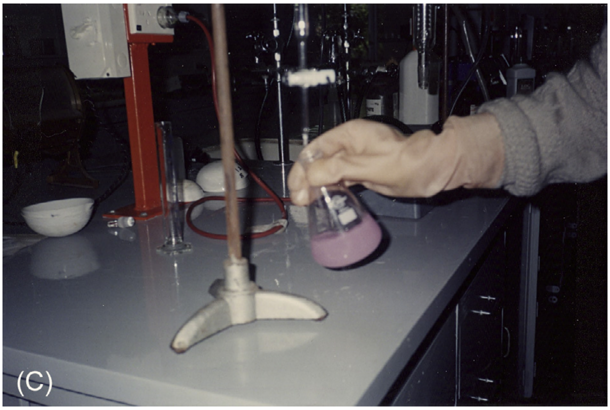

Fig. A3.1, Cont'd (C) Titration of benzoic acid standard solution.

A3.1.4 Calculation

$$\text{Free CaO} = \frac{(\text{TCaO} \times v)}{G} 100\% \tag{A3.2}$$

Where,

V = volume of benzene/carbonic acid/absolute alcohol solution consumed in titrating (ml)
G = weight of slag sample.

A3.2 Step 2 Determination of $Ca(OH)_2$ content in slag

A3.2.1 Equipment and apparatus

- **(i)** Strong sulfuric-acid gas-washing bottle;
- **(ii)** Drying tower containing 3–5 Å sieve sorbent;
- **(iii)** Drying tower containing magnesium perchlorate, ($Mg(C1O_4)_2$);
- **(iv)** Themocouple;
- **(v)** Thermolyne tube furnace, (120 V/10 A/1300 W);
- **(vi)** Quartz tube with “ground-glass” joints;
- **(vii)** Magnetic holder;
- **(viii)** Voltage regulator, (2000 W);
- **(ix)** U-tube containing silica gel;
- **(x)** U-tube containing magnesium perchlorate, ($Mg(ClO_4)_2$);
- **(xi)** Bottle with outlet port.

Fig. A3.2 presents the testing apparatus for determining the $Ca(OH)_2$.

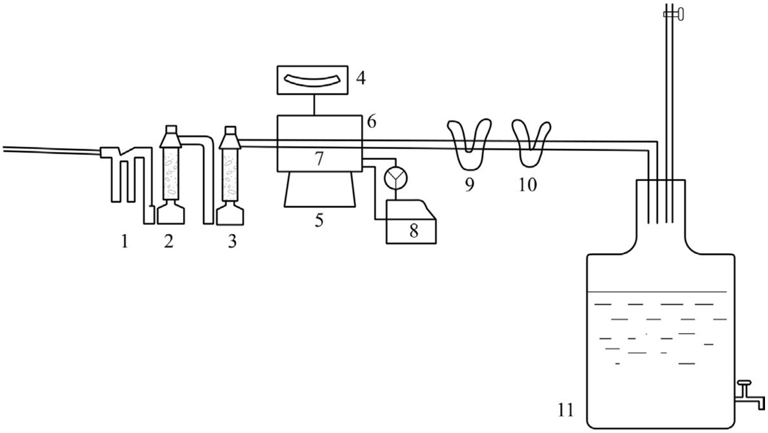

Fig. A3.2 Apparatus for testing $Ca(OH)_2$.

A3.2.2 Reagents

- **(i)** Sulfuric acid, (H_2SO_4, gravity = 1.84);
- **(ii)** Analytically pure absolute magnesium perchlorate ($Mg(ClO_4)_2$),
- **(iii)** Sieve sorbent, 3–5 Å;
- **(iv)** Analytically pure discolored silica gel.

A3.2.3 Procedures and calculation

- **(i)** Set up the equipment as shown in Fig. A3.2, and ensure that the tubes are airtight.
- **(ii)** Aerate dry air for 30 min., at 100 °C. Weigh the U-tube, aerate it for 15 min, and then weigh it again until the weight is constant, get W_0 (g).
- **(iii)** Weigh out a 0.5 g slag sample and transfer it to a magnetic holder. The sample should be dried for 2–3 h at 100 °C and kept in a drier prior to use. Push it into the quartz tube. Aerate it until the moisture at the ends of quartz tube vanish, weigh it, and then aerate it for 15 min. Weigh it again until the weight is constant, get W_1, (g). Find the free water content in the slag sample according to the following equation:

$$A = \frac{(W_1 - W_0)}{0.5} \times 100\% \qquad \text{(A3.3)}$$

- **(iv)** Increase temperature to 560 °C, and take another U-tube containing silica gel. Aerate it for 30 min, weigh it, aerate it for 15 min, and then weigh it again until the weight is constant, get W_0 (g).
- **(v)** Weigh out a 0.5 g separate slag sample and transfer it to the magnetic holder, push it into the quartz tube, aerate it until moisture at the ends of the quartz tube vanish, weigh it, aerate it for 15 min, and then weigh it until it is constant, get weight W_1, (g). Calculate the total content of free and combined water in the slag sample.

$$B = \frac{W_1' - W_0'}{0.5} \times 100\% \qquad \text{(A3.4)}$$

The $Ca(OH)_2$ content in the slag can be calculated from the following equation:

$$\mathrm{Ca}\left(\mathrm{OH}\right)_2\,\% = 4.111\left(B - A\right) \tag{A3.5}$$

Where,

4.111 is the molecular weight ratio of $Ca(OH)_2$ to water.

Actual free CaO content can be calculated by using the following equation:

$$\text{Free CaO} = \text{Total CaO}\% - 0.7567\ \mathrm{Ca}\left(\mathrm{OH}\right)_2\,\% \tag{A3.6}$$

where,

0.7567 = the molecular weight ratio of CaO to $Ca(OH)_2$

Appendix 4: Procedures to determine free magnesium oxide

The following method was adopted by the author in research studies to determine free MgO content in slag.

Similar to the free CaO test, the free MgO test has two steps. The first step is the determination of total magnesium oxide in the slag; the second step is the determination of the free magnesium oxide.

A4.1 Determination of Total Magnesium Oxide

A4.1.1 Reagents

- **(i)** 25 % Triethanolamine, ($(HOCH_2CH_2)_3N$);
- **(ii)** Ammonium Hydroxide–Ammonium chloride buffer solution, (NH_4OH–NH_4Cl);
- **(iii)** Bromothymol blue indicator;
- **(iv)** 0.025 N EDTA standard solution.

A4.1.2 Procedure

- **(i)** Pipet 50 ml pretreated sample solution (SiO_2 has been filtered off);
- **(ii)** Transfer to 450 ml beaker;
- **(iii)** Add 100 ml water and 6 ml triethanolamine;
- **(iv)** Mix up, then add 20 ml ammonium hydroxide-ammonium chloride buffer solution, (pH = 10);
- **(v)** Add seven drops of indicator;
- **(vi)** Titrate, adding EDTA to the solution until it becomes blue.

A4.1.3 Calculation

$$\mathrm{MgO\%} = \frac{\mathrm{TMgO} \times (V_2 - V_1)}{G \times \dfrac{50}{250} \times 1000} \times 100\%$$

Where,

$G \times \dfrac{50}{250}$ = Real weight of sample used, (g);

TMgO = Titration of EDTA to MgO, (mg/ml);
V_2 = EDTA consumed for CaO + MgO, (ml);
V_1 = EDTA consumed for CaO, (ml).

A4.2 Determination of Free Magnesium Oxide in Slag

A4.2.1 Reagents

- **(i)** Ethanoic acid - methyl alcohol solution;
- **(ii)** Ammonium chloride (NH_4C1, solid);
- **(iii)** Absolute alcohol;
- **(iv)** Hydrochloric acid, (HC1, 1:1, volumetric standard).

A4.2.2 Procedure

- **(i)** Weigh out 0.25 grams of the slag sample, minus 75 µm;
- **(ii)** Transfer the sample into a 250 ml beaker containing a 100 ml ethanoic acid - methyl alcohol solution, and equip the beaker with a magnetic stirrer.
- **(iii)** Add 1 gram of solid NH_4C1, place the beaker on a hot plate, and stir with a magnetic stirring bar at 65–70 °C for 30 min;
- **(iv)** Cool for 20 min. Wash residue with absolute alcohol 3–4 times by using a filter; after using a dense filter paper, discard the filter liquid;
- **(v)** Put the residue into a 300 ml beaker, add 1:1 hydrochloric acid to dissolve the residue, and transfer it to a 250 ml volumetric flask. Add water to dilute it to 250 ml, and mix the solution thoroughly;
- **(vi)** Pipet two samples at 25 ml each. Separately titrate samples with an EDTA solution to determine CaO content and total content of CaO and MgO. Then subtract the CaO content from the total content of CaO and MgO. The result is the free MgO content.

$$\text{free MgO} = \frac{\text{TMgO}\left(V_2 - V_1\right)\times 10}{G\times 1000}\times 100\%$$

Where,

TMgO = Equivalent weight (mg) of MgO per ml of EDTA;
V_1 = Volume of EDTA standard solution used for CaO, (ml);
V_2 = Volume of EDTA standard solution used for total CaO and MgO, (ml);
10 = Volume ratio of total solution to one sample;
G = Weight of slag sample (g).

Appendix 5: Nickel slag sampling protocol

The following protocol was developed to obtain representative samples of the nickel slag that was processed for Falcondo Aggregates, in Bonao, Dominican Republic. The recommended procedures were based on the general requirements of ASTM D75, "Standard Practice for Sampling Aggregates," and Ontario Ministry of Transportation LS-625, "Guidelines for Sampling of Granular Aggregates."

The procedures were prepared to obtain representative samples from the cooling face of the slag dump. From the ~30,000 tonnes of nickel slag produced each month, it is intended to develop a single stockpile of ~2000 tonnes, which can be further reduced to 200 tonnes for nickel slag sampling and testing. A 200-tonne conical stockpile was 12–14 m in diameter and 4.5 m high. Similarly, the 2000-tonne stockpile was 22–24 m in diameter and 7.5 m high.

As previously discussed, a test area was to be delineated in the field where only quality nickel slag was to be dumped for the sampling and test program. The height of the nickel slag embankment was in the order of 20 m, and that production over about two weeks was dumped over the crest of the embankment within a section of defined limits (about 100 m length in total). Over these two weeks, about half of the 30,000 ton produced per month was dumped, resulting in a layer of about 1.5 m of "fresh" nickel slag over the existing embankment (assuming a 2H:1V embankment side slope and unit weight of 2 tonnes/m^3 for the nickel slag).

It must be emphasized that at all times the nickel slag embankment/stockpile sampling must be completed in such a manner as to protect the safety of the sampling personnel.

A5.1 Sampling procedure

1. At the outset, it will be necessary to construct, using known materials, a pad ~600 mm thick and of sufficient size that the nickel slag obtained from the embankment can be stockpiled, mixed and then sampled for use in the testing program.
2. The face of the embankment is to be sampled using a stratified random sampling method. The face to be sampled must be divided into at least five equal length lots (ie, every 20 m or so approximately). The sampling locations (stations) within each lot then are to be selected randomly (using either a random number generator or tables) along the length of the face.

3. Wherever possible, and providing that the face is accessible safely to construction equipment and sampling technicians, sampling should be carried out by excavating a vertical channel, bottom to top, within each lot for the full height of the embankment face. The channel should extend to a depth of about 1.5 m, cutting through the "fresh" nickel slag and be sufficiently wide (about 3 m) to obtain ~400 tonnes of material from each channel location.
4. The material excavated from each channel is to be stockpiled separately on the prepared pad. These individual stockpiles (sublots) then are to be constructed using a front-end loader, with each bucket of material end-dumped over the top forming a conical stockpile.
5. Upon completion of the stockpile, a front-end loader or bulldozer should be used to flatten the stockpile to about a rectangular layer of about 1 m thick (14 m × 14 m square, for instance).
6. Two random numbers are to be picked using a random number table or generator to determine the sample location within the leveled layer. The first number is used to determine the longitudinal distance from the corner of the spread layer; the second number is used to determine the offset from the edge of the layer. The sample then is obtained by excavating through the full depth of the leveled layer. A total of five samples should be obtained in this fashion for each stockpile (sublot). These samples can be kept separately for testing, or combined to form a composite sample for the sublot.
7. The size of sample required for testing is somewhat dependent on the maximum nominal aggregate size. For instance, for 75 mm material, ASTM D75 recommends a minimum sample size of 150 kg (100 kg for 50 mm material; 75 kg for 37.5 mm; 50 kg for 25 mm; etc.).

Given the height and slope of the embankment, it is considered likely that channel sampling will not be practical or consistently safe at this location. If the embankment height and side slope does not permit safe channeling of a full-height vertical channel (even if completed in two or more stages, by reaching up from the bottom and then down from the top), it may be necessary to remove material from the base of the embankment carefully to initiate a controlled collapse of the face. The collapsed material then can be taken away from the face, remixed, leveled and sampled in conformance with Steps 5 and 6 above.

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Note: Page numbers followed by *f* indicate figures and *t* indicate tables.