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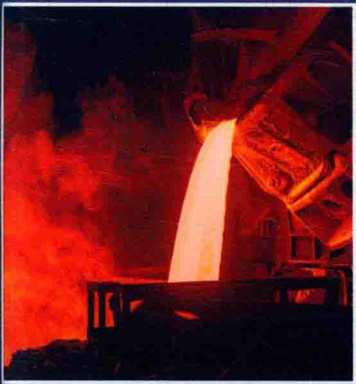

The Utilization of Slag in Civil Infrastructure Construction

George C. Wang

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WOODHEAD PUBLISHING

Woodhead Publishing Series in Civil and Structural Engineering: Number 68

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The Officers' Mess Business Centre, Royston Road, Duxford, CB22 4QH, UK
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, USA
The Boulevard, Langford Lane, Kidlington, OX5 1GB, UK

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

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

ISBN: 978-0-08-100994-9 (print)
ISBN: 978-0-08-100397-8 (online)

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

Publisher: Matthew Deans
Acquisition Editor: Gwen Jones
Editorial Project Manager: Charlotte Cockle
Production Project Manager: Omer Mukthar
Designer: Greg Harris

Typeset by SPi Global, India

The Utilization of Slag in Civil Infrastructure Construction

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.

I also wish to acknowledge the assistance provided by the library staff from Joyner Library of East Carolina University, particularly Mr. Joseph Thomas for reviewing related materials, and Ms. Rebecca Harrison for obtaining references; and the assistance provided by Professor Jo Ann Jones for providing valuable suggestions. The assistance of graduate students Wei Hu and Hua Liu in preparing the illustrations in this book is also acknowledged. Finally, thanks are extended to Charlotte Cockle of Elsevier, who assisted in managing the numerous text files before production; to Gwen Jones of Elsevier for her guidance throughout the process and for arranging the review and project presentation; and to Ms. Gothai Bakthavachalam, project manager of SPi, for overseeing the production of 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_1	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)

σ_e	expansion force of compacted mass steel slag per unit volume (N/m^3)
σ_{euv}	volume expansion force from steel slag which are unstable (N/m^3)
σ_n	normal stress acting on the surface of one steel slag particle (MPa)
σ_t	maximum tension stress of steel slag acting on potential disrupting region (MPa)
σ_v	virtual expansion stress
σ_v	virtual volume force (N/m^3)
σ_{vs}	side virtual expansion stress
σ_{vs}	virtual side expansion stress (MPa)
σ_x	normal stress
σ_y	normal stress
σ_θ	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

* 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