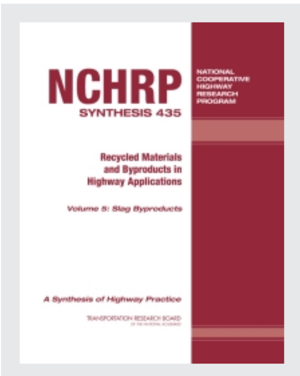

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 435

Recycled Materials and Byproducts in Highway Applications

Volume 5: Slag Byproducts

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP SYNTHESIS 435: Volume 5

Project 20-05, Topic 40-01

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Director
Transportation
Research Board

Recycled materials and industrial byproducts are being used in transportation applications with increasing frequency. There is a growing body of experience showing that these materials work well in highway applications. This study gathers the experiences of transportation agencies in determining the relevant properties of recycled materials and industrial byproducts and the beneficial use for highway applications. Information for this study was acquired through a literature review, and surveys and interviews with state department of transportation staff. The report will serve as a guide to states revising the provisions of their materials specifications to incorporate the use of recycled materials and industrial byproducts, and should, thereby, assist producers and users in "leveling the playing field" for a wide range of dissimilar materials.

Mary Stroup-Gardiner, Gardiner Technical Services LLC, Chico, California, and Tanya Wattenberg-Komas, Concrete Industry Management Program, California State University, Chico, California, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

The report is presented in eight volumes, the first of which is available in hard copy and on the Internet. The next seven volumes are available through the Internet only and can be found at: http://www.trb.org/Publications/NCHRPSyn435.aspx. The eight volumes are:

Volume 1 *Recycled Materials and Byproducts in Highway Applications—Summary Report*
Volume 2 *Coal Combustion Byproducts*
Volume 3 *Non-Coal Combustion Byproducts*
Volume 4 *Mineral and Quarry Byproducts*
Volume 5 *Slag Byproducts*
Volume 6 *Reclaimed Asphalt Pavement, Recycled Concrete Aggregate, and Construction Demolition Waste*
Volume 7 *Scrap Tire Byproducts*
Volume 8 *Manufacturing and Construction Byproducts*

CONTENTS

CHAPTER ONE

FERROUS BYPRODUCTS

Ferrous slags are the byproducts of the iron and steel making processes (Figure 1). Iron is obtained by combining iron ore, iron scrap, and fluxes (limestone and/or dolomite) in the blast furnace. The product from this furnace is pig iron, which can be used to fabricate products (e.g., cast iron) or as input for the steel making process. The byproduct from the first furnace is blast furnace slag (BFS), which is defined by ASTM as "the nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases that are developed in a molten condition simultaneously with iron in a blast furnace" (ASTM C989 2006).

Different cooling processes of the slag result in different BFS byproducts. Air-cooled BFS (ACBFS) is obtained when the BFS is poured into beds and slowly cooled under ambient conditions. A crystalline structure is formed and a hard, lump slag is the result. Cooling is accelerated by adding controlled amounts of water, air, or steam, which produces a byproduct with increased cellular structure. This byproduct is expanded or foamed BFS and is lightweight with high porosity. BFS cooled and solidified with water and air quenched in a spinning drum produces a pelletized BFS byproduct. Adjustments of the cooling process are used to increase or decrease the crystalline structure or to alter the glassy (vitrified) characteristics. Crystalline structures are desirable for use of the slag as an aggregate replacement; more vitrification (more glass content; amorphous) is needed for reactive cementitious applications. BFS that is cooled and solidified rapidly in water has little or no crystalline structure and has sand-sized particles. This byproduct is then crushed or milled into fine, cement-sized particles to produce granulated ground BFS (GGBFS).

The steel furnace uses the liquid blast furnace metal, scrap, and fluxes (lime, dolomitic lime) and high-pressure oxygen injection to produce a wide range of steel products. There are several points in this process where slag byproducts are collected. Steel furnace slag is defined by ASTM as the nonmetallic product consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium, and magnesium that is developed simultaneously with steel in a basic oxygen furnace (BOF), electric arc furnace (EAF), or open hearth furnace (OH). As with iron manufacturing, the steel making byproduct characteristics will depend on the type of furnace technologies. The most common types of steel slag byproducts are BOF slag, EAF slag, and ladle slag. Additional information can be found at the following websites:

- National Slag Association: www.nationalslag.org
- Slag Cement Association: www.slagcement.org
- Recycled Materials Resource Center website: www.rmrc.unh.edu/
- Turner–Fairbanks Highway Research Center website: http://www.fhwa.dot.gov/research/tfhrc/.

PHYSICAL AND CHEMICAL PROPERTIES

Because of the tight quality control and quality assurance (QC/QA) procedures in place for the primary iron and steel products, the characteristics of the byproducts are also very consistent in chemistry and quality at any given time. Steel manufacturers commonly use the slag chemistry to monitor process control (Yzenas 2009). The microstructure of the byproducts is strongly dependent on the type of furnace and the slag cooling process. Slag properties can vary widely between plants because of differences in the feedstock as well as technologies. One method for classifying slag byproducts is ASTM C989, which specifies three grades of GGBFS based on its reactivity, which is represented as the ratio of compressive strength of slag mortar cubes to reference cement mortar cubes and is referred to as the Slag Activity Index (Table 1).

Table 2 provides typical ranges for oxides in iron and steel slags. Unslaked lime (CaO) in contact with moisture can result in expansive and potentially exothermic reactions, while magnesia can result in slower long-term expansion characteristics.

Table 3 provides some limited information on trace metals in EAF slag. No data were found for BFS byproducts; however, it is expected that BFS will contain a variety of trace metals including chromium, copper, lead, and zinc (Chesner et al. 2000).

ENGINEERING PROPERTIES

Table 4 provides an indication of the range of typical physical properties for some of the blast and steel furnace slags. The ACBFS is most commonly used as an aggregate replacement

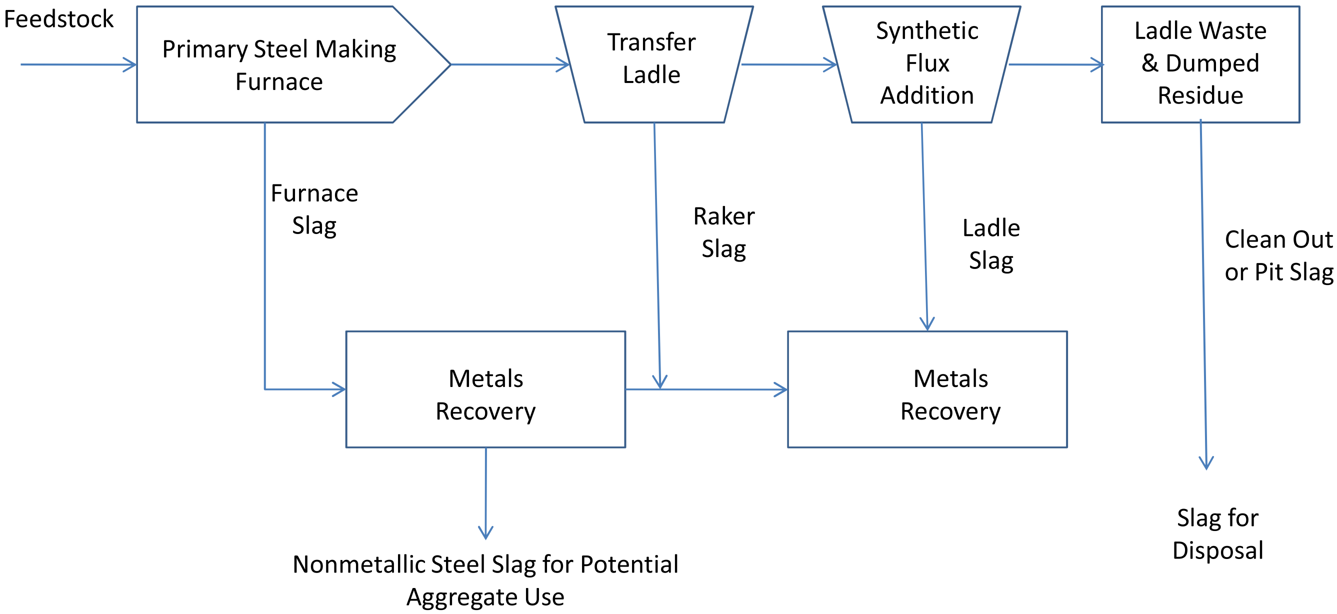

FIGURE 1 Slag production from steel making plant (after RMRC 2008a).

TABLE 1
SLAG ACTIVITY INDEX REQUIREMENTS OF ASTM C989

Slag Activity Index, min. %	Slag Activity Index, minimum %	
	Average of Last Five Consecutive Samples	Any Individual Sample
7-day index		
Grade 80	—	—
Grade 100	75	70
Grade 120	95	90
28-day index		
Grade 80	75	70
Grade 100	95	90
Grade 120	115	110

After Fehling et al. (2008).
— = data not available.

(RMRC 2008a). Examples for iron and steel slag byproducts are found in Table 5. Because of its porous nature, ACBFS tends to have a lower thermal conductivity than conventional aggregates, whereas steel slags are dense with a high heat capacity.

ENVIRONMENTALLY RELATED PROPERTIES

BFS byproducts slurried in water are mildly alkaline, with pH values between 8 and 10 and a small amount of elemental sulfur. Steel slag can exceed a pH of 11, which will be corrosive to aluminum or galvanized steel pipes. In some cases, a tufa-like precipitate can form on the surface of steel slag. This is the result of leachate combining with atmospheric carbon dioxide, which forms the precipitates and can cause clogging of drains in water control systems (RMRC 2008a). Occasionally, leachate from BFS

TABLE 2
TYPICAL OXIDES IN IRON AND STEEL SLAGS

Compounds	Blast Furnace			Steel Slags	
	BF Slag, %	GGBFS (Germany)	GGBFS (UK)	BOF Slag, %	EAF Slag, %
Calcium Oxide (CaO)	32 to 45	39.2	40	43	35
Silicon Oxide (SiO_2)	32 to 42	40.0	35	15	14
Iron Oxide (Fe_2O_3)	0.1 to 0.75	1.8	0.2	25	29
Magnesium Oxide (MgO)	5 to 15	3.6	10	8	8
Manganese Oxide (MnO)	0.2 to 0.8	—	—	5	6
Aluminum Oxide (Al_2O_3)	7 to 16	13.5	12	5	5
Sulfur Oxide (SO_3)	0.4 to 2.0	0.2	—	0.07	0.1

After Yzenas (2009).
— = data not available.

TABLE 3
TRACE ELEMENTS REPORTED FOR IRON AND STEEL SLAGS

Trace Metals	BFS	EAF Slag (mg/kg)
Ag	None found in literature	4
As		3.4
Ba		370
Cd		1.1
Cr		1100
Hg		0.12
Mn		23 000
Ni		30
Pb		56
Se		1.1
V		190
Zn		370

Chesner et al. (2000).
BFS is from the first furnace.
EAF is from the steel (second) furnace.

byproducts can have a yellow/green color with a sulfurous odor and is likely a function of slow moving or stagnant water in contact with the slag. Stagnant water usually has high concentrations of calcium and sulfide. When in contact with oxygen, the sulfides precipitates out as elemental sulfur and produce calcium thiosulfate (Chesner et al. 2000). The typically reported leachate concentrations from BFS byproducts are below EPA hazardous waste criteria (Table 6).

USAGE AND PRODUCTION OF IRON AND STEEL SLAGS

United States

In 2003, approximately 19 million tons of domestic iron and steel furnace slags were used in the United States.

TABLE 4
TYPICAL ENGINEERING PROPERTIES OF IRON AND STEEL SLAGS

Physical Property		BF Slag	Steel Slag		Test Method
		ACBFS	BOF	EAF	
Open Graded					
Specific Gravities	Dry	2.450–2.550	3.300–3.400	3.300	ASTM C127/128: Density, Specific Gravity, and Absorption
	SSD	2.550–2.650	3.350–3.475	3.400	
Water Absorption, %		3 to 7	1 to 2 Coarse	1 to 2 Coarse	ASTM C566: Moisture Content by Drying
			2 to 4 Fine	2 to 4 Fine	
Dry Strength, ksi		19–22.5	61.8	56	AS 1141.22: Australian Test Method for Wet/Dry Strength Variation
Wet Strength, ksi		14.6–20.3	51.7–67.4	54–67.4	
Wet/Dry Strength Variation, %		10 to 20	5 to 20	5 to 15	
Micro Deval, %		15 to 22	12 to 18	16	ASTM D6928: Degradation by Abrasion
Polished Aggregate Friction Value (PAFV)		53	58 to 63	58 to 63	ASTM D3319:Accelerated Polishing of Aggregates
Sodium Sulfate Soundness, %		5	<4	<4	ASTM C88: Soundness of Aggregates
Dense Graded Aggregate Material					
Maximum Dry Density, lb/ft^3		128.0 to 134.2	143.6 to 149.8	143.6 to 149.8	ASTM D698: Compaction Characteristics of Soils
Optimum Moisture Content, %		8 to 12	8 to 12	8 to 12	

After Yzenas (2009).
SSD = saturated surface dry.
BFS is from the first furnace; EAF is from the steel (second) furnace.

TABLE 5
TYPICAL ENGINEERING PROPERTIES FOR IRON AND STEEL SLAGS

Property	Iron Slag ACBFS	Steel Slag (type not identified)
LA Abrasion, %	35–45	20–25
Sodium Sulfate Soundness, %	12	<12
Angle of Internal Friction	40^{o}–45^{o}	40^{o}–50^{o}
CBR, %	Up to 250	Up to 300
Hardness (Moh's)	5–6	6–7

After RMRC (2008b).
CBR = California bearing ratio.

TABLE 6
TYPICAL LEACHATE PROPERTIES FOR IRON AND STEEL SLAGS

Constituents	Toxicity Characteristic Leaching Procedure (TCLP)		
	Blast Furnace Slag (Iron)	Electric Arc Furnace Slag (Steel)	Regulated Level (mg/L)*
Ag	0.09	<0.1	5.0
As	0.14	<0.01	5.0
Ba	2.18	<0.5–3.3	100.0
Cd	0.03	<0.05	1.0
Cr	0.15	<0.02	5.0
Hg	0.002	<0.0004	0.2
Ni	—	<0.01–0.11	—
Pb	0.23	0.026–0.12	5.0
Se	0.12	<0.01	1.0

RMRC (2008b); Chesner et al. (2000).
TCLP evaluates toxicity.
*http://www.ehso.com/cssepa/TCLP.htm.
— = no information.

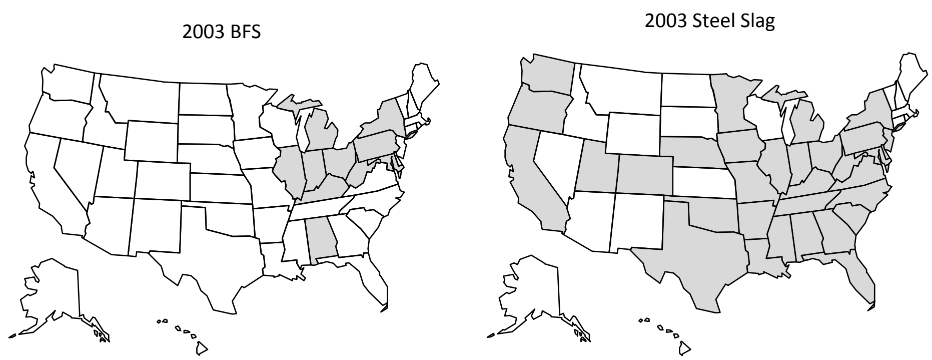

FIGURE 2 Sources of iron and steel slags in 2003 (Yzenas 2009).

About 75% of these slag byproducts were sold for use in construction applications (Yzenas 2009). There were about 23 slag-processing companies serving both the iron and steel industries or processing old slag stockpiles. Iron slag was available at about 40 sites in 15 states and steel slag at about 90 sites in 32 states (Yzenas 2009). Figure 2 shows states with iron (BFS byproducts) and steel slag availability.

International

About 75% of the BFS production in the United Kingdom is converted into GGBFS with the remainder converted into ACBFS, both of which are almost exclusively used in concrete applications. These byproducts constitute approximately 1.5% of the total U.K. aggregate production, which is estimated at about 236 millions of tons annually.

CHAPTER TWO

AGENCY SURVEY RESULTS

The agency survey question for iron and steel slag byproduct usage is shown in Table 7, along with the number of states reportedly using each of the byproducts. This table shows that the most commonly used iron slag byproduct is GGBFS in portland cement concrete (PCC) applications. Steel slag is used primarily in hot mix asphalt (HMA) applications and pavement surface treatments. ACBFS is used in bound applications by some states in HMA, surface treatment, and PCC applications. Unbound usage of ACBFS includes embankment and drainage applications. A number of states indicated a generic use of BFSs in a range of applications, with embankments being the most common. Table 8 and Figure 3 show the states using the iron and steel byproducts.

TABLE 7
RESULTS FOR AGENCY SURVEY FOR IRON AND STEEL SLAG BYPRODUCTS USED IN HIGHWAY APPLICATIONS

Slag Byproducts: Is your state using, or has ever used, these byproducts in highway applications?
If you are not sure of the specific type of slag that has been used in your state, check the Slag, unknown type at the bottom of the list.

- Blast furnace slag: by product from iron and steel manufacturing
- Air-cooled blast furnace slag: liquid slag cooled slowly
- Granulated BFS: molten slag cooled and solidified by rapid water quenching to a glassy state
- Expanded BFS: Molten slag to which air, water, or steam is added to foam (light weight)
- Vitrified, pelletized BFS: molten slag cooled and solidified with water, air quenched in spinning drums

Byproducts	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embank.	Flowable Fill	HMA	Pavement Surface Treatment (non-structural)	PCC	Soil Stability
Blast Furnace Slag	0	1	1	6	1	5	3	3	2
ACBFS	0	0	3	4	0	6	6	4	0
GGBFS	0	1	1	1	6	2	0	30	2
Expanded BFS	0	0	0	0	0	0	0	1	0
Vitrified, Pelletized BFS	0	0	0	0	0	0	0	0	0
Steel Slag	0	1	0	3	0	13	4	2	0
Unknown Type	1	1	1	1	1	2	2	1	1

Embank. = embankment.

TABLE 8
STATES USING IRON AND STEEL BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

Number of Applications	States					
	BFS (General)	ACBFS	GGBFS	Expanded BFS	Steel Slag	Unknown Type of Slag
6	—	—	—	—	—	—
5	WV	IL, IN	—	—	—	ID
4	UT, VA	OH	—	—	—	—
3	—	—	AL, PA	—	IN	—
2	KY, WI	KY, PA, VA	KS, KY, MS, NJ, OH, TX, WA	—	MO, OH, SC, WI	AK
1	AL, MD, NJ, NY, VT	FL, MO, NJ	AR, CT, DC, DE, FL, ID, IL, IA, LA, ME, MN, MO, NC, NE, NH, NY, OK, OR, SC, VA, VT, WI, WV	IL	AL, CO, CT, DC, IL, IA, KY, MN, OR, PA, VA, WV	DC, FL, MA

— = data not reported.

FIGURE 3 States using iron and steel slag byproducts in highway applications as of 2009: (a) blast furnace slag; (b) air-cooled blast furnace slag; (c) granulated ground blast furnace slag; (d) steel slag.

CHAPTER THREE

LITERATURE REVIEW: FERROUS BYPRODUCTS

Information from the National Slag Association (NSA 2006) website showed a number of typical uses of slag byproducts in highway applications (Table 9). Information provided by Wang and Emery (2004) summarized these applications in a flow chart that links typical materials replaced with slag and the associated applications (Figure 4).

APPLICATIONS—BOUND

Portland Cement Concrete

Boltz (1998) evaluated the material properties of rigid pavements constructed in Ohio on I-50 with GGBFS (25%) for improved durability. Difficulties with timely cutting of the joints owing to the lower heat of hydration in GGBFS mixtures when paving in cold temperatures delayed the project curing times. He also recommended avoiding the use of these mixtures under these environmental conditions.

Ansari et al. (2000) reported that New Jersey commonly used GGBFS in concrete mixtures to reduce expansive reactions from alkali–silica reactivity (ASR) by reducing the alkali content needed for the deleterious reactions.

Brameshuber and Schrider (2001) found that an additional activator was needed in conjunction with the GGBFS to obtain sufficient early strength of the mix. The activator for GGBFS is typically the cement, but the addition of fly ash or cement kiln dust can also be used to promote an alkaline, or to a minor extent, sulfate activation. The ability to produce cement with good early strength is dependent on the additional materials and the GGBFS mineralogies and chemistries.

Griffiths and Krstulovich (2002) noted that Illinois considers GGBFS to be a mineral admixture that is a component of blended cements with a lower heat of hydration and a cap of 25% GGBFS was noted in this document.

Eggers (2002), at the Louisiana Transportation Research Center, noted that the Louisiana Department of Transportation and Development approved the use of GGBFS Grade 120 in pavements and structures. The article reported that there were only two pavements and one structural project that used GGBFS, and there was only one source of the Grade 120 GGBFS. GGBFS Grade 100 was investigated to determine if it provided similar PCC properties as the Grade 120 by evaluating set times, compressive strength, modulus of elasticity, freeze/thaw resistance, expansion, creep, scaling, and abrasion resistance.

Nobata and Ueki (2002) reported on the use of BFS and GGBFS in PCC applications in Japan. The authors noted that while the initial interest in the byproducts was for controlling alkali–aggregate reactions and reducing the heat of hydration, the environmentally friendly aspects of reducing CO_2 emissions was becoming increasingly important (Table 10). Japan has established three grades of BFS (Table 11). Of the three grades, B is most commonly used. The surface area of the slag is also controlled for various applications (Table 12).

Campbell (2003) applied for a U.S. patent for the use of slag in concrete for a French company. The patent covers a method for limiting the release of organic materials into the environment during the construction of foundations by using a BFS ground very fine (2,500 to 5,000 Blaine fineness).

Jin and Yazdani (2003) evaluated blended cements for use by the Florida Department of Transportation (DOT). A blend of fly ash, slag, and chemical admixtures was used in two typical Florida hot weather concreting PCC mix designs. This preliminary research report indicated that the small sample size in the study and the variability of PCC fresh and hardened properties prevented any firm conclusions.

Concrete Construction (2004) reported that Pennsylvania State engineers expected to obtain a concrete deck that would last up to three times as long as PCC without byproduct additives such as fly ash, silica fume, and GGBFS.

Leshchinsky (2004) noted that ACBFS was used as a sand replacement in an Australian ready-mix concrete. The author noted the slag needs to be added to the mix in increments to achieve a uniform appearance. Fresh concrete testing is needed to make sure the blended cement has acceptable standards. Benefits for using slag sand are cleanliness (limited fines), vesicular structure and water saturation condition, less segregation during transportation, less bleeding, and reduced problems with plastic shrinkage. Disadvantages included less workability of the slag sand PCC after pumping than conventional mixes, it was more difficult to finish, and had an inconsistent rate of absorption of air entraining admixtures.

Ling et al. (2004) evaluated the use of GGBFS in high-performance concrete in China, where the annual production

TABLE 9
USAGE BASED ON RECOMMENDATION FROM THE NATIONAL SLAG ASSOCIATION (2007)

Application	ACBFS	Pelletized	GGBFS	Steel Slag
Asphalt Aggregate	X			X
Concrete/Masonry Aggregate	X	X		
Blended Cement			X	
Clinker Production	X			X
Roof Aggregate	X			
Railroad Ballast	X			X
Gabions/Rip Rap	X			X
Lightweight Fill	X	X		
Fill	X			X
Roadway Base		X	X	
Stabilized Soil			X	
Roller Compacted Concrete			X	
Environmental Applications	X			X

X = indicates byproducts used in each application.

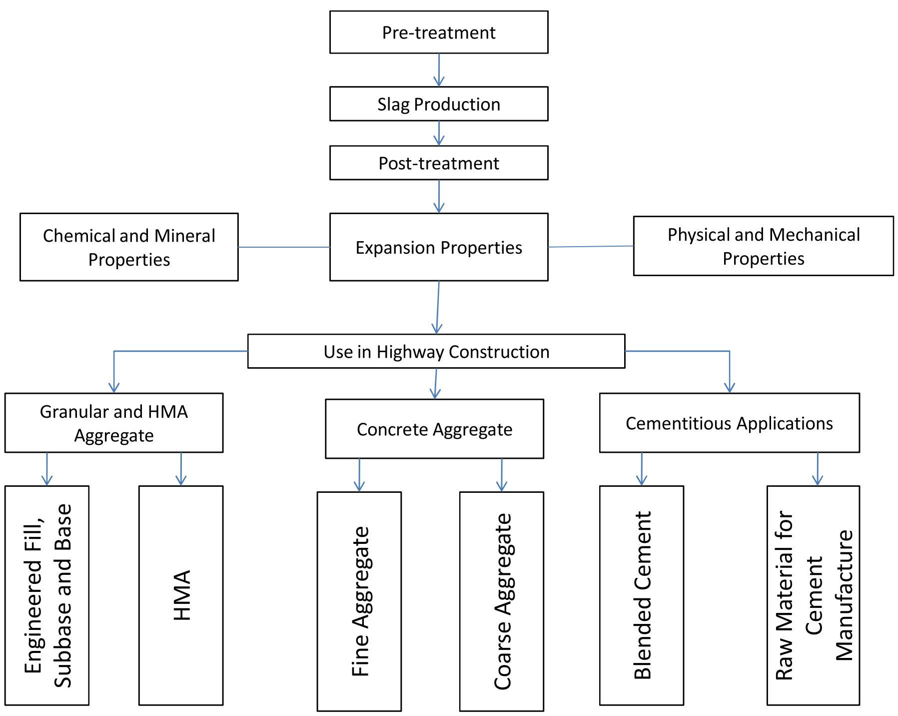

FIGURE 4 Schematic of slag byproducts and uses (after Wang and Emery 2004).

TABLE 10
VOLUME GENERATED OF CO_2 PER TON OF CEMENT

Information		Ordinary Cement (Col A)	Portland BFS Grade B (Col B)	Reduced Volume, % [Col (A-B)/A]
Quantity of Limestone Used, kg		1,092.0	60.6	45
Consumed Energy	Coal, kg	103.6	57.8	44
	Electric Power, kWh	99.2	72.6	27
Volume Generated of CO_2, kg		775.6	437.0	44

After Nobata and Ueki (2002).

TABLE 11
STANDARD GRADES FOR BFS IN JAPAN

Kind	Weight of BFS
Grade A	Above 5 and below 30
Grade B	Above 30 and below 60
Grade C	Above 60 and below 70

After Nobata and Ueki (2002).

TABLE 12
SURFACE AREA REQUIREMENTS FOR GGBFS IN JAPAN

Kind	Surface Area, cm^2/g
GGBFS 4,000	Above 3,000 and below 5,000
GGBFS 6,000	Above 5,000 and below 7,000
GGBFS 8,000	Above 7,000 and below 10,000

Nobata and Ueki (2002).

of GGBFS is approximately 15 million tons. Testing showed that hardened concrete properties increased with increasing fineness of the GGBFS.

In 2004, the South Carolina DOT listed GGBFS in PCC as approved for routine use in highway construction. In addition, the report identified the EPA recommendations that procuring agencies revise their guide specifications to require contract specifications for individual construction projects or products to allow for the use of coal fly ash or GGBFS unless the use of the materials are technically inappropriate for a particular application. The South Carolina specifications allow for the one-to-one replacement of cement with GGBFS up to 50% of the cement.

Moosberg-Bustners (2004) investigated the use of steel slag as mineral filler in self-consolidating concrete in Sweden. The study used three steel slags: disintegrated argon oxygen decarburisation (AOD), EAF, and ladle slags. Quartz with a maximum particle size of 0.045 mm was used as the reference material. The major chemical compounds are shown in Table 13. Free CaO and MgO can cause durability problems when they are present in steel slag used in PCC applications. The hydration of the CaO is an exothermic reaction and can cause cracking of the hardened cement paste. The MgO slowly hydrates into brucite, which is an increasing volume reaction that will crack the paste and thereby reduce the integrity and strength of the PCC.

TABLE 13
MAJOR CHEMICAL CONTENT OF DIFFERENT STEEL SLAGS

Oxide	% by Weight of Steel Slag			
	AOD	EAF	LD	Cement
SiO_2	34	27	14.3	22.3
CaO	47	54	42.5	64.8
MgO	6	6	12.7	0.8
Al_2O_3	2.3	4.9	22.8	3.4
FeO	2	2.6	1.5	4.3

After Moosberg-Bustners (2004).
LD = ladle slag.

Wet grinding of the EAF and AOD slags was evaluated as a method for slag modification. Heat of hydration-related parameters was used to evaluate changes in reactivity of the steel slag byproducts. The variable, t_o is the time of transition between dormant and accelerating periods of reactivity, and t_{max} is the time of maximum heat (Table 14). The results show wet grinding activates slag reactions (shorter time to maximum heat.

Table 15 shows the PCC compressive strengths of the various slag mixtures. The steel slag mixes and control and quartz mixes have similar compressive strengths at 28 days ($w/c = 0.61$). At the higher w/c ratio, the steel slag mixes have higher 23-day strengths than either the control or quartz. Shrinkage characteristics were not influenced by the use of steel slags. The conclusions drawn by the authors were that the wet grinding of the steel slag minimized expansive reactions and improved the long-term strength gain of the PCC.

An additional method for improving the reactivity of steel slag by increasing the glass content by remelting and rapidly cooling the slag was evaluated. The result of this method of processing steel slag significantly increased the reactivity of the EAF and substantially decreased the reactivity of the AOD (Table 16). Shorter times to t_o and t_{max} correspond to faster rates of hydration.

Manso et al. (2004) conducted research on oxidized EAF slag with the intention of using the byproduct as fine and coarse aggregates in PCC applications. Acceptable hardened and leachate testing results were obtained. Manso et al. (2005) also investigated ladle furnace slag, finely ground, for use in different applications. The authors suggest that this slag could be used in masonry mortars and low-traffic-volume roadways.

Videla and Gaedicke (2004) investigated the use of GGBFS in high performance concrete (HPC), which requires

TABLE 14
INFLUENCE OF PROCESSING OF STEEL SLAG BYPRODUCTS ON REACTIVITY

Material	t_o, minutes	t_{max}, minutes
EAF, dry ground	140	760
EAF, wet ground	150	640
EAF, dried, wet ground	150	720
AOD, dry ground	170	710
AOD, wet ground	120	500
AOD, dried, wet ground	180	730
Quartz	140	650
Quartz, wet ground	100	520
Quartz, dried, wet ground	170	760
Cement, pure	140	650

After Moosberg-Bustners (2004).

TABLE 15
PROPERTIES FOR PCC WITH VARIOUS STEEL SLAG BYPRODUCTS AFTER WET GRINDING

Mix	Compressive Strength, psi			
	w/c	1-day	7-day	28-day
Cement	0.48	1,784	5,395	7,672
	0.61	1,363	5,221	6,305
	0.81	1,001	3,379	4,119
Quartz 20%	0.61	1,320	4,105	6,962
Quartz 40%	0.81	740	2,437	4,554
EAF 20%	0.61	1,146	4,119	6,715
EAF 40%	0.81	827	2,973	5,192
AOD 20%	0.61	914	4,424	6,483
AOD 40%	0.81	638	3,075	4,946

After Moosberg-Bustners (2004).

a 28-day compressive strength of 8,700 to 16,000 psi. Results showed that the American Concrete Institute (ACI) equation for predicting modulus of elasticity did not work well for GGBFS mixtures. The measured moduli were lower than the predicted values. The ACI standard square root equation for estimating flexural strength from compressive strength also did not work well for GGBFS mixtures (ACI 2005). An updated model for predicting shrinkage was also needed. Laboratory testing of the mixtures showed that the standard ASTM C944 test for abrasion was not an effective method of assessing the properties of the GGBFS mixtures.

A Canadian Best Practices Guide was developed by Bouzoubaâ and Fournier (2003) that describes the use of both fly ash and GGBFS in concrete mixtures. The guide includes information on the definition, typical material characteristics, lists of appropriate standards, effect of supplementary cementitious materials (SCMs) on concrete properties (fresh and hardened), content recommendations, impact on production, placing and finishing, curing considerations, and QC requirements. GGBFS was defined "as a non-metallic product consisting essentially of silicates and aluminosilicates of calcium and other bases that are developed in a molten condition simultaneously with iron in a blast furnace, then water-chilled rapidly to form glassy granular particles, and then ground to cement fineness or finer." The primary source of GGBFS in Canada is found in Ontario, and it is related to the iron production by the Dofasco and Stelco company in Hamilton and Nanticoke, and Algoma Steel in Sault Ste. Marie. These operations produce approximately 530,000 tons per year of GGBFS.

TABLE 16
INFLUENCE OF REHEATING AND COOLING (GRANULATION) OF STEEL SLAG BYPRODUCTS ON REACTIVITY

Material	t_o, minutes	t_{max}, minutes
EAF, slag	140	760
EAF, granulated	110	600
AOD, slag	170	710
AOD, granulated	260	930

After Moosberg-Bustners (2004).

The Canadian standard CSA A3000-04 limits the SO_3 and sulfide sulfur contents to 4.0% and 2.5%, respectively, to minimize problematic expansive sulfate reactions. The particle size of the GGBFS is controlled in the grinding process. Smaller particles of less than 0.010 mm contribute to early strength gains, while particles in the 0.0100 to 0.045 mm range provide later-age strength gains. GGBFS particles larger than 0.045 mm contribute little to the cementitious properties. The MgO (brucite) content, evaluated with autoclave expansion testing, is limited to minimize disruptive reactions. Key mineralogy focuses on the glass content of the GGBFS, which helps regulate the reactivity of the slag. The physical properties are shown in Table 17.

The use of GGBFS in fresh concrete improves the workability and cohesiveness, has little influence on bleeding, can reduce the heat of hydration when the fineness is less than 6,000 cm^2/g and at levels of 50% (65% in warm temperatures), and can increase setting times. The increased setting times can alter the finishing work schedule and the slower strength gain tends to make the GGBFS mixtures more sensitive to cold weather conditions. If the fresh concrete is not properly cured, PCC mixes with GGBFS may carbonate more than conventional PCC.

The GGBFS can result in lower 28-day compressive strengths owing to the slower strength gains, little influence on the drying shrinkage, and reduced long-term creep as a result of the increased long-term strength and elastic modulus. PCC mixes with GGBFS tend to have improved resistance to chloride ion penetration and sulfate resistance, but slightly less resistance to deicing salt scaling and little influence on freeze/thaw characteristics.

TABLE 17
TYPICAL PROPERTIES OF GGBFS

Properties	Typical Range of Properties	CSA A3000
Specific Gravity	Approx. 2.9	—
Particle Size	<0.010 to >0.045 mm	20% max. greater than 0.045 mm
Blaine Surface Area, cm^2g	4,000 to 6,000	—
Autoclave Expansion	—	0.8% maximum increase in length
Glass Contents	80% to 100%	—

After Bouzoubaâ and Fourner (2003).
— = data not reported.

The Canadian CSA A23.1 standard requires the use of a minimum of 15% of SCMs (fly ash, GGBFS, or a combination) if the weather is at or below 41°F (5°C) and 25% if the weather is at or above 81°F (27°C). Table 18 shows proposed minimum percentages by mass of slag for a range of portland pozzolana cement applications and weather conditions.

Construction issues noted in this report included the potential:

- Need for increased silo storage for GGBFS compared with portland cement because of the differences in specific gravities (3.15 for cement; 2.9 for GGBFS).
- Adjustment of plant air pressures to minimize fugitive dust issues resulting from the lighter specific gravities.

PCC mixes with less than 25% SCM make it easier to finish the surface, whereas mixes with low *w/cm* ratios and more than 30% SCMs create finishing problems because of the low bleeding characteristics of the mixes and longer times before the finishing can be completed.

QC of PCC with less than 35% SCMs are the same as for conventional PCC products. Additional requirements needed when the amount is greater than 35% are:

- Water to cementitious materials (*w/cm*) ratios 0.05 lower than for conventional PCC application
- Increased curing times
- *w/cm* ratio maximum limitations
- Prequalified testing (trial mix) program
- Mill certificates from SCM producer with each shipment
- Mix design review
- Increased QC testing, at least at the start of the project.

Table 19 summarizes the steps needed for QC programs when SCMs are used in the concrete production. Each stakeholder's responsibilities are outlined in this table.

Taylor et al. (2006) evaluated laboratory testing methodologies for identifying potentially unacceptable ingredients in PCC applications. The findings showed that some traditional tests are capable of identifying incompatibilities within the first 30 minutes of mixing because of rapid aluminates/sulfate balance problems. Other tests are not capable of detecting longer-term issues with silicate hydration problems. No test included in the study was capable of identifying both problems. The authors also reported that there was no clear threshold value that indicated compatibility or incompatibility and that a value considered poor for one application is acceptable for another application. The most valuable contribution of the testing was considered the ability to monitor the uniformity of the materials over time. The tests can be used for both prequalification and field monitoring of the product during construction (i.e., QC/QA) and included recommendations for foam index, foam drainage, slump loss, unit weight, semi-adiabatic temperature monitoring, setting time, and chemistry of reactive materials.

The foam index test is used to evaluate the stability of the air voids system in the PCC. In this test a small quantity of water and cement are placed in a jar and agitated. Air entrainment admixture is then added and agitated again. The optimum combination is when the air bubbles exist uniformly across the surface of the liquid. The foam drainage test uses a kitchen blender to mix air entrainment admixtures with water and cement, and the foam is poured into a graduated cylinder. The amount of water in the cylinder over time is determined.

Sippel and Cramer (2005) investigated the use of three percentages (0%, 30%, and 50%) of GGBFS (Grade 100) as a SCM for Wisconsin concrete applications. GGBFS concrete achieved comparable strengths to conventional concrete after 56 days. Scaling of the concrete increased with increasing percentages of GGBFS and appeared to be related to the carbonation at the surface of the samples. PCC with 50% GGBFS resulted in unsatisfactory pavement performance as a result of scaling (deicer freeze/thaw scaling resistance) problems. A level of 30% GGBFS appeared to provide acceptable performance, but depended on the specific PCC components and curing conditions. The authors noted that traditional curing methods may not be effective with GGBFS concretes.

The Missouri DOT (MoDOT) has a history of only allowing low concentrations (<25%) of GGBFS in concrete

TABLE 18
PROPOSED MINIMUM PERCENT OF SLAG IN VARIOUS PCC APPLICATIONS

Type of Application	Minimum Percent Slag, %	
	Cold Weather	Hot Weather
General Applications	15	25
Mass Pour Concrete	50	65
Exposed to Sulfate	35–50	35–55
ASR Issues	35	35
Hand Finishing Concrete Flat Work Exposed to Chloride and Freeze/Thaw Conditions	35 max	50 max

After Bouzoubaâ and Fournier (2003).

TABLE 19
SUMMARIZES THE QC CHECKLIST FOR ALL PARTIES

Function	Owner	SCM Producer	Ready-Mix Producer	Contractor
Mix design(s)	Review as to compliance with specifications and representative nature of supporting test results	Provide recommendations for amount of cementing materials required at SCM replacement levels for equivalent strength	Conduct trial mixes in laboratory	Coordinate review
	Check that required SCM replacement is achieved		Prepare mix design(s)	Assure approval from owner is obtained.
Pre-qualification program on mix design(s)	Review results		Conduct trials in field at early stages of concreting	Arrange for trial mixes in field
	Assure that representative age:strength curves are available so that site early age strengths can be checked			Use trials to develop early age strength test calibration.
Initial field trial to performance of mix's plastic properties	Witness site trials		Cooperate with contractor in conducting trials	Arrange for program
				Involve placers and finishers
Testing during initial concreting	Assure that testing is to specification		Increase QC testing of air content	Manage finishing crew timing
	Require increased testing during initial concreting			
Mill certificates	Review	Provide submittal with data for LOI and 0.045 mm size	Review and adjust QC and mix design to account for shift in SCM properties	Coordinate distribution of results
		Advise if shift in properties needed		
In situ strength monitoring				Conduct tests if data on early strength is a requirement.
Review QC test results	Conduct review			
	Assure other parties are aware of results			

After Bouzoubaâ and Fournier (2003).
LOI = loss on ignition.

mixes. MoDOT teamed with researchers at the University of Missouri–Rolla to study PCC properties at higher levels of GGBFS for low heat of hydration concretes. A level of 70% was approved for the Creve Coeur Bridge. Results showed that the compressive strength of the 70% GGBFS concrete was about 2,000 psi lower than the plain Type I cement mix. The use of a high-range water reducer helped reduce the difference to 1,300 psi. Findings indicated that sufficient activators are required to achieve the desired strength, freeze/thaw durability and chloride permeability decreased, and scaling potential increased. Slag percentages of between 40% and 60% appear to be closer to the optimum level for the highest strength gains. Recommendations from the study included:

- Specifications need to focus on only those parameters that are of interest for the particular project.
- Curing procedures for freeze/thaw durability testing need to be adjusted for slag mixes.
- Adoption of a scaling test requirement is required.
- Comprehensive mix design testing is required.
- High slag content mixes need to be refined and adjusted at the mix design stage.
- Different levels of durability factors are to be set for different applications (e.g., bridge decks, substructures, and pavements).

Lane (2006) tested 36 bridge decks for the condition and quality of the concrete. Fly ash and slag blends had some of the lowest water absorption rates of the concretes tested, although the initial petrographic rating would indicate higher absorption characteristics. A recommendation was made to include measurements of the water transportation characteristics of concrete in both the materials acceptance and asset evaluation and management programs.

In Japan, Anwar and Yamada (2007) conducted standard assessments of compressive and flexural strengths, porosity, and durability on PCC mixes with GGBFS.

The NSA (2006) reported on the use of BFS as coarse aggregate in thin concrete overlays (white topping) in

TABLE 20
INFLUENCE OF STEEL SLAG ON PCC PROPERTIES

Properties	Percent of Steel Slag Used to Replace Fine Aggregate				
	0	15	30	50	100
Slump, inches	3.1	3.1	2.8	2.8	0.0
Compressive Strength, 28 days, psi	3,771	4,786	4,496	4,061	3,336
Compressive Strength, 90 days, psi	4,061	5,076	5,439	7,107	6,092
Compressive Strength, 180 days, psi	4,859	5,439	5,947	6,382	6,527
Flexural Strength at 28 days, psi	276	587	653	653	580

After Qasrawi et al. (2008).
w/c = 0.5.

Wayne County, Michigan. The BFS met the requirements for an ASTM No. 57 stone with a density of about 125 lb/ft^3. Approximately 25% of the coarse aggregate was replaced with the slag.

Barnett et al. (2007) investigated using BFS in concrete for fast track construction. A 70% cement replacement was needed to drop the peak temperature rise. Maturity functions that account for the lower ultimate strength obtained at elevated curing temperatures were identified as being the most useful for estimating actual strength development.

Qasrawi et al. (2008) used low CaO steel slag (EAF) as a fine aggregate replacement in various percentages in PCC mixtures because steel slag with low calcium oxide contents have little to no reactivity when used in PCC mixtures. Table 20 shows that above 50% of slag replacing the fine aggregate the workability of the fresh concrete is lost (i.e., slump is 0) and flexural strength is decreased. The optimum percent of replacement appears to be between 15% and 30% of steel slag.

Buch and Jahangirnejad (2008) investigated the thermal expansion properties of various Michigan PCC mixes with limestone, dolomite, slag, gravel, and trap rock. The thermal expansion coefficient values ranged from 4.51 to 5.92 με/°F and were significantly influenced by the geology of the components in the concrete. This research was considered important because this coefficient is one of the inputs required by the new FHWA mechanistic–empirical pavement design method for rigid pavements. The results in Table 21 confirmed the previously reported values found in their literature review.

Texas Transportation Researchers Juenger et al. (2008) developed guidelines for identifying slow setting mixtures and preventing their use in pavements. Mix designs with setting times longer than 10 hours also had 1-day compressive strengths of less than 500 psi. Texas currently only has requirements on the 7-day strengths of 3,200 to 3,500 psi, which the blended cement mixes with long set times met. One day testing was recommended to identify unacceptably slow setting blends.

Fehling et al. (2008) evaluated blended cement for producing ultra-high performance concrete. One of the main issues with preparing the blended cement was the requirement for specialized equipment by the contractor. The authors suggested premixing the microfine portland cement clinker, BFS grains, and synthetic silica to ensure proper handling, blending, dosage, and uniformity of the final product.

Roske et al. (2008) evaluated 13 trial mixtures for their potential for improved durability. The best performing proportions for the most effective mixes were 30% GGBFS, 10% metakolin, 12% ultra-fine fly ash, or 9% silica fume by weight of cement replacement. The criteria for selection considered cost, mechanical properties, and durability.

Cement Australia (2009) reported on the use of GGBFS as an SCM in two ranges of slag: 20% to 40% and 60% to

TABLE 21
EXAMPLES OF THERMAL EXPANSION COEFFICIENTS FOR PCC MIXES

Concrete Components	Thermal Expansion Coefficient, με/°F	Coefficient Increased with Time?*
Limestone	4.51–4.54	3.9 to 4.8 at 365 days
Dolomite Coarse Aggregate	5.87–5.92	3.8 to 4.8 at 365 days
Gravel	5.84	5.5 to 5.8 at 365 days
Slag	5.71	5.5 to 5.8 at 365 days
Trap Rock (gabbro)	5.41	4.8 to 4.9 at 365 days

After Buch and Jahangirnejad (2008).
*Values estimated from graphs in reference.

70%. The low slag PCC is used for general construction, while the high slag content PCC is used where the heat of hydration and resistance to chloride, sulfate, or seawater penetration needs to be considered.

Cement Australia (2009) also reported the use of ACBFS as an aggregate, which is accepted for use based on standard aggregate properties. The fact sheet notes the ACBFS properties, while within acceptable limits, differ with slightly lower densities, higher water absorption, better shape, rougher texture, lower wet strengths, higher LA abrasion values, and less potential for ASR reactions.

Rangaraju and Desai (2009) studied the use of fly ash and slag concrete to resist damage from potassium acetate-based deicers, which generate ASR expansive reactions. Mid-range fly ash replacements between 25% and 35% and slag content of 50% provided the best resistance to deicing chemicals.

The Slag Cement Association (SCA 2009) website provided a summary of projects in the United State that have been constructed with slag SCM (Table 22).

Hot Mix Asphalt

In 2000, Hunt and Boyle completed a report on the use of steel slag in HMA applications for the Oregon DOT. Test sections with 30% slag and without steel slag were constructed in 1994, and the performance was monitored for five years. The aggregate fraction between the 12.5 to 6 mm (½ to ¼ inch) was replaced with the steel slag (Table 23). The immediate concern for the Oregon DOT was the significant increase in the specific gravity of the steel slag. Since HMA is ordered and placed on a unit of tons of mix, the same mass of the HMA with steel slag resulted in a reduction in coverage of 30% (i.e., a thinner lift of HMA was placed). The unit weight of the conventional HMA was 158 lb/ft^3, while the slag mix was 170 lb/ft^3. The authors noted that 0.20 ton/ft (17 ft wide by 2-in. thick mat) was needed for conventional mix; 0.23 ton/ft was required for the steel slag section. A Hveem mix design was used to select the optimum asphalt content (Table 24). Acceptable mix properties were obtained with the slag mixes.

The authors noted that while the LA abrasion values appeared to be acceptable, they are not sure the test is appro-

TABLE 22
SUMMARY OF HIGHWAY AND BRIDGE PROJECTS WITH SLAG

Project Name	City	State	Description
Project–RCC Roadway	Midfield	AL	RCC Roadway
Arkansas Highway Dept. Project #50030	Newark	AR	One of the first uses of slag cement in highway department projects
Arkansas Highway Dept. Project #50030	Batesville—Highway 167 South	AR	One of the first uses of slag cement in highway department projects
Arkansas Highway Dept. Project #50030	Batesville—Highway 167 South	AR	One of the first uses of slag cement in highway department projects
State Road 300	Crisp County	GA	State road construction
Owensboro Bridge	Owensboro	KY	Bridge supports and deck over the Ohio River
US Highway 11 Lake Pontchartrain Bridge	New Orleans	LA	Bonded overlay of historic bridge, 5 miles long and 2 lanes wide
LA Highway 182 Bridge over Charenton Canal	Charenton	LA	LA DOTD’s first HPC Bridge
Livernois Road Reconstruction	Wattles to Braemer Roads, Troy	MI	2001 paving job
Livernois Road.Reconstruction—Innovation/Best Use Award	Wattles to Braemer Roads, Troy	MI	2001 paving job
Big Beaver Road Reconstruction—Innovation/Best Use Award	Troy	MI	2001 paving project
Wabasha Bridge	Minneapolis	MN	Pier foundations and stems
Creve Couer Lake Memorial Bridge	St. Louis	MO	Several foundations 13.6' x 26' x 72'
Pennsylvania Highway 0222-003	Shillington	PA	New highway construction
Intersection Improvements Route 17	Newport News	VA	Intersection improvements
U.S. Highway Route 58 Widening	Courtland	VA	State highway expansion
Virginia Route 44 Widening	Virginia Beach	VA	Limited access road widening
Interstate 95 Widening	Fredricksburg	VA	Interstate highway paving at I-95 & Route 17
Interstate 664 Paving	Hampton	VA	Interstate highway paving
Interstate 64 Widening (1983–1987)	Hampton	VA	Interstate highway paving
Virginia Highway “Smart Road” Bridge (VDOT)	Wilson Creek in Montgomery County	VA	Post-tensioned CIP bridge: Research for Intelligent Transportation System technologies
Mercury Boulevard Improvements	Hampton	VA	Commercial paving at Interstate 64 & Mercury Boulevard
Mass concrete bridge beam casting bed	Roberts	WI	Casting bed, mass concrete
Wisconsin DOT bridge structure	Waupaca	WI	Bridge structure using 40% slag cement
SP 6290-05-74 Highway 10 Bridge	Amherst	WI	Multiple bridge project on a newly constructed state highway

After Slag Cement Association (2009).
HPC = high performance concrete; CIP = cast-in-place.

TABLE 23
AGGREGATE PROPERTIES FOR OREGON HMA TEST SECTIONS

Tests	Test Method	Spec. Limits	Aggregates	
			Natural Aggregate	Steel Slag
Bulk Specific Gravity	AASHTO T85	—	2.69	3.63
Bulk Specific Gravity, SSD	AASHTO T85	—	2.74	3.68
Apparent Specific Gravity	AASHTO T85	—	2.81	3.82
Water Absorption, %	AASHTO T85	—	1.54	1.35
LA Abrasion, %	AASHTO T96	30% max.	16.3	24.2
Oregon Air Degradation	OSHD TM208	Pass No. 20 < 30%	Pass No. 20 = 11.4%	Pass No. 20 = 6.7%
		Sed. Ht. < 3.0 in.	Sed. Ht. = 0.3 in.	Sed. Ht. = 0.2 in.
Sodium Sulfate, %	OSHD TM206	12% max.	1.5	0.6
Gradation, Cumulative Percent Passing, %				
Sieve Size, mm				
19.0			100	100
12.5			98	100
9.50			55	94
6.30			2	49
4.75			1	20
2.00			1	3
0.425			1	1.9
0.075			0.5	0.9

After Hunt and Boyle (2000).
SSD = saturated surface dry.

priate for slag evaluation. The Oregon air degradation test assesses the quantity and quality of material generated by attrition similar to that produced on the roadway under traffic.

Construction notes from the HMA plant operator showed he had to increase the plant temperature by 0.75°F for the slag mixtures, compared with the conventional HMA. The field crew noted that the steel slag mix held a warmer temperature longer and that density could not be achieved until the mix had dropped below 160°F. Post-construction skid testing showed that the skid numbers after five years were 49 for the control section and 53 for the steel slag sections. The international roughness index (IRI) was 84 and 82 in./mi for the control and steel slag sections, respectively. After five years the IRI values were 91 and 81 in./mi, respectively. The Oregon DOT's conclusions after five years were that the sections were performing in a similar manner.

The project costs were an important consideration for the Oregon DOT. The haul distance for acquiring the steel slag was 36 miles, and the haul cost was $8.33/ton. In addition to the $3.50/ton for material cost (unscreened), a 10% contractor markup for the material, and a $3.00 Oregon DOT credit for the natural aggregate, the total cost of the slag was $10.14/ton (circa 1994 basis for costs). If the gradation of the steel slag needed to be altered the cost per ton would increase to from $5.50 to $7.50.

Illinois researchers, Griffiths and Krstulovich (2002) indicated that ACBFS provides improved skid resistance when

TABLE 24
SUMMARY OF HMA PROPERTIES FOR OREGON MIXTURES

Property	Class B Mix Design Criteria	Natural Aggregate Mix	Steel Slag Mix
Gradation, Cumulative Percent Passing, %			
25.0 mm	99–100	100	100
19.0 mm	92–100	96	96
12.5 mm	75–91	80	80
9.5 mm	—	68	76
6.0 mm	50–70	53	59
2.0 mm	21–41	27	24
0.425 mm	6–24	12	11
0.075 mm	2–7	5	4.6
Binder Content, %	4–8	4.7	4.9
Specific Gravity	—	2.4	2.593
Air Voids, %	5.5–6.5	4.5	4.7
VMA, %	≥14	14.2	14.7
Hveem Stability	≥37	36	36
Moisture Sensitivity, % retained	≥75	88	95

After Hunt and Boyle (2000).
— = no information.

used in HMA surfaces. As of August 1999, Illinois added a self-testing producer control program requirement for HMA. Slag is tested as an aggregate; slag must meet the LA abrasion requirements.

Griffiths and Krstulovich (2002) also noted that Illinois reported using steel slag as a coarse aggregate in HMA and surface treatments because of its favorable frictional properties, high stability, and resistance to stripping (moisture damage) and rutting. Potential issues with harmful reactions to aluminum or galvanized metals in the slag were noted. Some QC problems when using steel slag resulted in the addition of a self-testing producer control program to the specifications.

The South Carolina DOT (2004) allows for the use of chrome and steel slag in HMA applications for low-volume roadways where there is a lack of quality crushed aggregate. The expansive nature of the steel slag needs to be addressed for successful use. The slag is required to meet the standard requirements for fine and coarse aggregates. HMA testing needs to include an evaluation of moisture sensitivity.

LaForce (2005) investigated the use of steel slag and Trinadad Lake Asphalt in a 12-mile overlay HMA application on I-70 in Glenwood Canyon, Colorado, over a post-tensioned slab on top of a retaining wall. Special testing required by the Materials Engineer included the standard testing for Hveem stability, air voids, voids in mineral aggregate, asphalt content, and density, as well as additional performance-related testing including both the Hamburg Wheel Tracking Device and French Rut Tester estimates of rutting, moisture sensitivity (Lottman Method), and in-place permeability. Aggregate testing included special fractured face, absorption, deleterious materials, and angularity tests for the steel slag (Table 25). Performance problems noted in the sections were attributed to low compaction at the joints and not to the material properties of the mix.

TABLE 25
PROPERTIES OF STEEL SLAG

Properties	Value
Bulk Specific Gravity	3.01
Water Absorption, %	4.20%
LA Abrasion, %	18
Gradation, Cumulative Percent Passing, %	
12.5 mm	92
9.5 mm	80
4.75 mm	52
2.36 mm	33
1.18 mm	23
0.60 mm	17
0.30 mm	13
0.15 mm	—
0.075 mm	6.9
Maximum sulfur content	2.5%

After LaForce (2005).
— = data not reported.

Stabilized Soils

Singh et al. (2008) evaluated combinations of fly ash and GGBFS in PCC stabilized mixtures. Their findings indicated that an increase in either the fly ash or GGBFS increased the maximum dry density; however, it is still lower than traditional natural materials with similar particle sizes. Increasing percentages also significantly increased the California bearing ratio (CBR) values of the soil.

Gupta (2008) evaluated the use of a combination of lime and granulated BFS at a replacement level of between 10% and 25%. CBR values ranged from 48 to 92, unconfined compressive strengths from 213 to 570 psi. Adding gypsum to the lime/GGBFS mix further improved the CBR and strength. Advantages suggested for using these blends for stabilization included lower energy requirements, since only dry grinding of material is needed and they resulted in lower costs. The author projected a cost savings of 30% for projects within about 20 miles of the byproduct source.

APPLICATIONS—UNBOUND

Synthetic Aggregates

Research by Padfield (2004) in the United Kingdom showed that the treatment of GGBFS with carbon dioxide gas at ambient temperatures and pressures can be used to produce synthetic aggregates with aggregate impact values in the range of 14 to 17 and loose densities of around 1.0, which would classify them as potential lightweight aggregates.

Transformation of Marginal Material

Pouya et al. (2007) explored the potential for activating BOF slag using plasterboard gypsum waste and cement bypass dust without using traditional portland cement in the binder. The crushed gypsum sulfate provided the activation for the BOF slag. The optimum percentage of the BOF slag was significantly influenced by the percentage of the bypass dust.

Base and Fill

The National Slag Association (2007) reported on the use of expanded slag for eliminating subgrade settlement at bridge abutments on Highway 17 northwest of Ottawa. The in situ clay had a high plasticity when the moisture content rose above optimum with evidence of high settlements. Normal weight aggregates (125 to 135 lb/ft^3) were expected to cause long-term problems with subgrade deformations. The Ministry of Transportation specified lightweight expanded slag with a density of around 73 lb/ft^3.

Legislation—European

Nobata and Ueki (2002) reported that two laws have been enforced in Japan since April 2001. The purchase of BFS cement specified for public works is based on the Green Purchase Law. PCC with BFS contents higher than 30% are designated as an environmentally related product with priority for procurement. The Common Specifications of Construction Works listed BFS cement Grade B for piles driving at a building site.

A position paper developed by Euroslag (2006) identified several key court cases that could influence the classification and use of slags. Palin Granit case law (September 2003) and Saetti and Frediani Order (January 15, 2004) clarified criteria for determining whether, in a series of defined circumstances, quarry byproducts should be considered a waste. Briefly, the criteria identified by the court indicated that if a material has an economic value it is a byproduct not a waste. A byproduct is not a production residue (i.e., waste) if the producer intends to market the byproduct without any further processing prior to reuse. The byproduct needs to have a strong likelihood of reuse.

In 2007, Waste and Resources Action Programme (WRAP) noted that the European Commission communication provided guidance for "competent authorities in making case by case judgments on whether a given material is a waste or not" (WRAP 2007a). This communication used BFS as a material falling outside of the definition of "waste." The European Environment Agency further defined the conditions where a production residue would not be considered a waste by posing three questions:

1. Is the further use of the material a certainty and not a mere possibility? If certain use cannot be guaranteed for all materials (i.e., applications) concerned, then the material should start as a waste.
2. Can the material be used again without any further processing? If an additional recovery process is required before further use, even if such subsequent use is certain, this is evidence that the material is a waste until the process has been completed.
3. Can the material be used again as part of the product process? However, further processing that is carried out as an integral part of the production process will not prevent the material from being considered as a byproduct. The case law indicates a narrow rather than a broad approach to the notion of production process; however, each material must be considered on a case-by-case basis.

Environmental

Several environmental issues were outlined in the 2007 WRAP paper. The use of BFS can result in the reduction of CO_2 emissions by about 50% as a result of replacing the cement with BFS in concrete production. Granulation of the BFS releases lower levels of hydrogen sulfide (H_2S), which are associated with the water quenching operations. The GGBFS operations need to be upgraded to limit emissions. The use of ACBFS in unbound aggregate applications may generate environmental problems as a result of bacterial or chemical action under specific conditions, such as poorly drained soils. In this case, the leachate can contain sulfides and other undesirable compounds. BFS leachate testing will have a potential for elevated concentrations of chloride, sulfate (i.e., S leaching as SO_4), alkali earth metals, and ammoniacal nitrogen. Heavy metals are typically below detection limits. The sulfur in BFS is bound inside of the internal matrix and is not available for leaching. The only sulfate available for contamination will be on the surface of the particles and then it is only a problem if it comes into contact with water. Typically, less than 1% will be leachable.

A risk assessment of constituents of interest were compared with the U.S. regulatory health-based benchmarks and included antimony, beryllium, cadmium trivalent and hexavalent chromium, manganese, thallium, and vanadium. None of these compounds were found in concentrations designated to be a health hazard by European standards. The WRAP 2007 paper provided a summary of the risk assessment results for slags (Table 26).

TABLE 26
RISK ASSESSMENT OF BFS: PRODUCTION STORAGE AND USE PHASES

Hazardous Event and Potential Pathway	Receptor(s)	Risk Before Mitigation			Issues and possible mitigation measures required at each phase (1 = production, 2 = storage, 3 = use)	Risk After Mitigation		
		H	M	L		H	M	L
Noise	People and the local environment			X X X	1. No issues identified but local authority planning permission controls should be adhered to. 2. No issues identified. 3. No issues identified.			X X X
Odor	People and the local environment		X X	X	1. Production of hydrogen sulfide from quenching and cooling processes can generate complaints from the general public. In-line granulation significantly reduces such odor and the potential for these types of complaints. 2. Once BFS has solidified and been processed into aggregates, there are no odor release issues. 3. If BFS is not applied correctly, it is theoretically possible for such odor releases (from leachate generation), although they are likely to be very minor. No direct evidence in relation to odor emerged during this study.			X X X
Spillage	People and the local environment			X	1. Good housekeeping required at handling and processing facilities in line with PPC permit conditions. 2. Good housekeeping at storage facilities required. 3. Good housekeeping required during usage/application stage.			X
Contaminated Run-off/Release of Contaminated Site Drainage to the Environment	Properties Ecosystems Surface water Ground water		X X X		1. Possible run-off issues from all BFS production activities are subject to PPC permit conditions. Reference should be made to BACMI/Environment Agency guidance. 2. All BFS stockpiles (pre-sales) are located within an integrated works complex and regulated via PPC permit conditions; refer to BACMI/Environment Agency guidance. Stockpiles must be within contained areas or similar with controlled/enclosed good draining systems. Control and clean-up spillages of material required. 3. BFS delivered to construction sites for use in unbound applications should be stored according to BACMI/Environment Agency guidance. BFS used in asphalt or concrete poses no environmental risk because the slag is fully bound by bitumen or cement.			X X X
Wind-borne Litter	People Properties Ecosystems			X X X	1. Good housekeeping required to prevent possibility of becoming airborne. 2. As above 3. As above			X X X
Airborne Dust, Powders or Particulars	People Properties Ecosystems			X X X	1. Coarse grain defined as >2 mm material. 2. As above 3. As above			X X X
Combustion Potential of BFS	People Properties Ecosystems			X	Not applicable as melting point of BFS is $>1,400^{o}$C.			X
	Atmosphere Surface water Ground water							
BFS Storage	People Properties Ecosystems			X	BFS delivered to construction sites for use in unbound applications should be stored according to BACMI/Environmental Agency guidance. BFS used in asphalt or concrete poses no environmental risk because the slag is fully bound by bitumen or cement.			X
BFS Disposal	People Properties Ecosystems			X	Not applicable—full usage of material during all phases of production, storage, and use.			X

After WRAP (2007a).
H = high risk; M = medium risk; L = low risk; PPC pollution prevention and control; BACMI = British Aggregate Construction Materials Industries.

CHAPTER FOUR

NONFERROUS SLAG BYPRODUCTS

While a number of research publications were found for work conducted in the United States, a number of international documents were also identified in the literature for iron and steel slags. Similar trends in research relating to steel slag usage were also seen (Figure 5). The highway applications researched in the literature are shown in Figure 6. The most prevalent use researched was for the use of BFS in PCC applications; only limited research on their use in geotechnical and HMA applications was found. By comparison, steel slag research focused mostly on its use in HMA applications followed by PCC and geotechnical applications.

Nonferrous slags are produced during the recovery and processing of nonferrous metals from natural ores (RMRC 2008a). Figure 7 shows a general schematic for the steps in the process. Phosphorous slag is the result of a secondary process (Figure 8).

As with steel slag, the byproduct ends up as either a rock-like or granular material. Three groups of nonferrous byproducts were listed on the RMRC (2008a) website:

1. Copper and nickel slags,
2. Lead/zinc slags, and
3. Phosphorous slags.

There are three basic steps in copper, nickel, and lead/zinc processing:

1. Roasting, which is heating below the melting point;
2. Smelting, which melts the roasted material; and
3. Converting, where the metal is separated from purities.

Phosphorous, copper, nickel, and zinc slags can be air-cooled or granulated (RMRC 2008a; TFHRC 2009). Often, molten slag is dumped into a pit and allowed to cool. When the slag is cooled rapidly by quenching with water a vitrified frit-like granulated slag is obtained. The result is a more uniformly shaped small particle that is more reactive than air-cooled. Air quenching results in the solidification of larger masses. Copper slag that is produced by smelting the copper concentrates in a reverberatory furnace is referred to as reverberatory copper slag. The cooling rate strongly influences the internal grain structure of the slags and mineralogy, which, in turn, influences the physical properties.

PHYSICAL AND CHEMICAL PROPERTIES

Physical properties are dependent on the type of slag, method of production, type of furnace, and cooling procedures associated with the production processes (TFHRC 2009). The chemical constituents and compounds found in various nonferrous slags are cited in Table 27.

ENGINEERING PROPERTIES

Engineering properties were collected from several sources. These properties are shown in Table 28.

ENVIRONMENTALLY RELATED PROPERTIES

The United Kingdom classified slags from primary and secondary production of zinc as hazardous waste and the reclassification of landfills in July 2004 was expected to significantly increase the cost of landfilling these materials. Leachate testing on cores and site-prepared cubes (7 days) showed that the heavy metal concentrations were below required limits and similar to control samples. The lead levels were also below detection limits, arsenic levels were negligible, and the zinc levels were higher for the zinc slag core samples but similar for cube results and below acceptable limits in this study.

USAGE OF NONFERROUS SLAGS

Use in the United States

In 2000, only 12 states indicated that nonferrous slags were produced in their state. Oregon and Nebraska produced fewer than 100,000 tons per year (Chesner et al. 2000). Montana, Texas, Missouri, Michigan, and Pennsylvania produced between 100,000 and 500,000 tons per year and Arizona, Idaho, New Mexico, Tennessee, and Utah produced more than 500,000 tons per year. As of 2000, only California had reported research activities on nonferrous slags; however, it did not have the potential for a supply of the byproduct.

International Use

Table 29 indicates the countries with some use of nonferrous slags as reported by Chesner et al. (2000). As of 2003, the BZL Works was the only zinc smelter in the United Kingdom, and had been in operation for about 50 years.

FIGURE 5 Sources of research for iron and steel slag usages in highway applications.

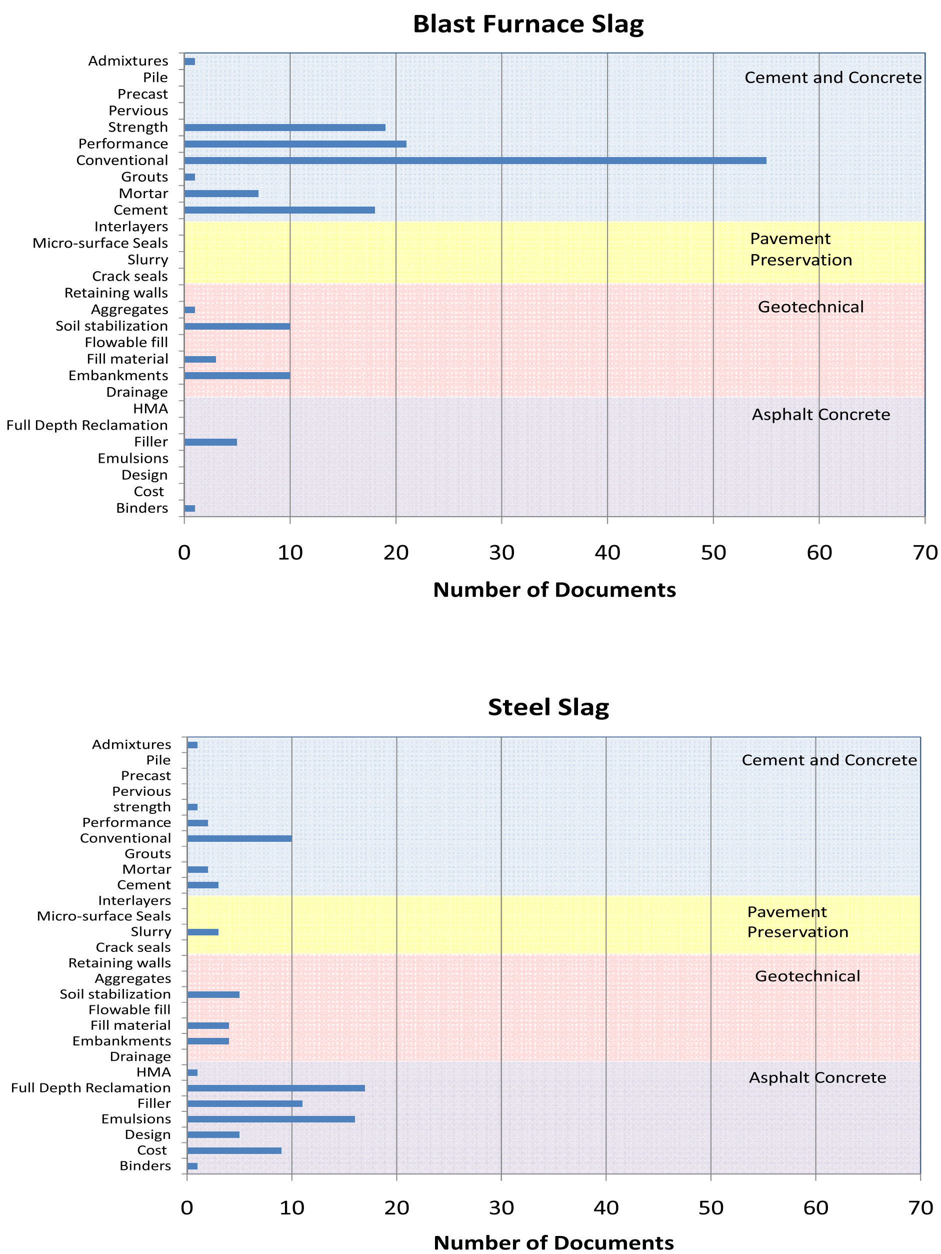

FIGURE 6 Applications for BFS iron and steel slag byproducts in highway applications found in the literature.

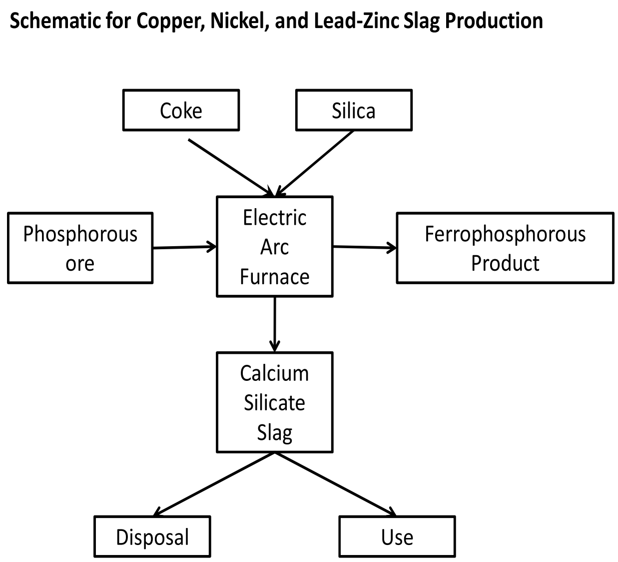

FIGURE 7 Schematic for nonferrous metals production (RMRC 2008a).

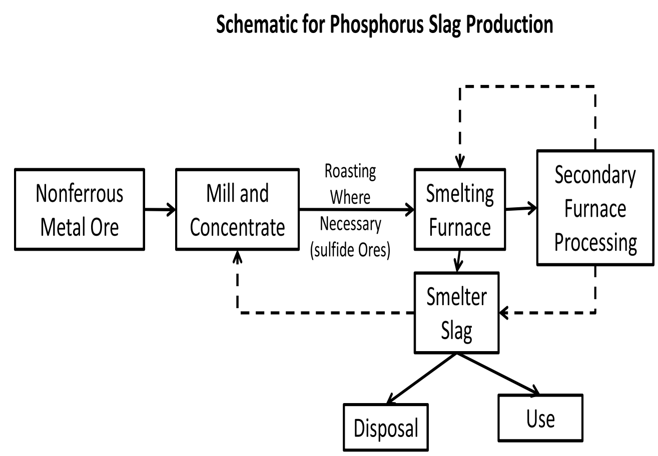

FIGURE 8 Schematic for phosphorous slag production (RMRC 2008a).

TABLE 27
EXAMPLES OF NONFERROUS SLAG COMPOUNDS

Constituent	Reverberatory Copper Slag (%)	Nickel Slag (%)	Phosphorus Slag (%)	Lead Slag (%)	Lead–Zinc Slag (%)
Al_2O_3	8.1	trace	8.8	—	6–7
As	—	—	—	—	0–5
BaO	—	—	—	—	2
CaO	2	3.96	44.1	22.2	14–20
Free CaO	—	—	—	—	—
Cu	0.37	—	—	—	0–5
Fe	—	—	2.8	—	37–40
Fe_2O_3	—	53.06	—	—	—
FeO	35.3	—	—	28.7	—
K_2O	—	—	1.2	—	—
MgO	—	1.56	—	—	1–1.3
MnO	—	trace	—	—	1–3
P_2O_5	—	—	1.3	—	—
Pb	—	—	—	—	1–2
PbO	—	—	—	—	0.8
S	0.7	—	—	1.1	2.8
SiO_2	36.6	29	41.3	35	19–20
SO_3	—	0.36	—	—	—
Zn	—	—	—	—	9–12

After TFHRC (2009).
— = data not reported.

TABLE 28
TYPICAL ENGINEERING PROPERTIES OF NONFERROUS METAL BYPRODUCTS

Properties	Copper Slag		Nickel Slag		Phosphorous Slag		Lead, Lead/Zinc, or Zinc Slag	
	Crushed Air-Cooled	Granulated	Crushed Air-Cooled	Granulated	Crushed Air-Cooled	Granulated	Crushed Air-Cooled	Granulated
Color	Black		Reddish Brown to Brown–Black		Black to Dark Gray		Red to Black	
Texture	Glassy	Small Pores	Angular, Smooth, Amorphous		Flat Elongated Glassy, Sharp Fractured Faces	Regular Shape, Angular	Glassy, Sharp, Angular, Cubical	
Blaine Fineness, cm^2/g	1,700		N/A	N/A	N/A	N/A	N/A	N/A
Specific Gravity	2.8–4.0	Lower than air-cooled	N/A	N/A	N/A	N/A	N/A	N/A
Unit Weight, lb/ft^3	175–237	N/A	219	N/A	85–90	85–90	N/A	156–255
Absorption, %	0.13	N/A	0.37	N/A	1.0–1.5	1.0–1.5	N/A	N/A
Angle of Internal Friction	Up to 53^{o}	N/A	Around 40^{o}	N/A	N/A	N/A	N/A	Up to 5^{o}
LA Abrasion, % Loss	22.1		24.1		<30		N/A	N/A
Sodium Sulfate Soundness, % Loss	0.90		0.40		<1		N/A	N/A

Source: (Pavez et al. 2004; RMRC 2008a; TFHRC 2009).
N/A = data not available

TABLE 29
INTERNATIONAL USES OF NONFERROUS METALS

Country	Utilization Category	Type of Application
Finland, Netherlands	General use	Asphalt concrete Granular base
Finland	Limited use General use	Cold mix asphalt concrete Embankment
Great Britain	Limited use	Stabilized base

Source: Chesner et al. (2000).

Operation shut down in 2003. When in operation, the annual production was about 99,200 tons of zinc, 33,070 tons of lead, and 88,185 tons of ferro-silicate slag, referred to as Imperial Smelting Furnace slag. The years of operation of this plant left a sufficient quantity of landfill/stockpiled byproduct.

Chile has seven copper smelter plants and the metal is obtained by pyrometallurgical extraction. In 2002, a total of 1,677,718 tons of fine copper was produced.

CHAPTER FIVE

AGENCY SURVEY RESULTS

The agency survey question for collecting information on the use of nonferrous slag in highway applications is shown in Table 30. Only one state indicated using phosphorous slag in an HMA application. Six other states mentioned that they are using slag of an unknown type in a range of highway applications (Table 31).

TABLE 30
RESULTS FOR AGENCY SURVEY FOR NONFERROUS SLAG BYPRODUCTS USED IN HIGHWAY APPLICATIONS

Type of Byproduct	No. of State Agencies								
	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embank.	Flowable Fill	HMA	Pavement Surface Treatment (non-structural)	PCC	Soil Stability
Copper and Nickel	None reported								
Lead, Lead-Zinc, and Zinc	None reported								
Phosphorous	0	0	0	0	0	1 (KY)	0	0	0

Embank. = embankment.

TABLE 31
STATES USING NONFERROUS SLAG IN HIGHWAY APPLICATIONS IN 2009

Number of Combinations of Byproducts and Highway Applications	States			
	Copper and Nickel	Lead, Lead-Zinc, and Zinc	Phosphorous	Unknown Type of Slag
6	None reported	None reported	—	ID
5			—	—
4			—	—
3			—	—
2			—	AL
1			KY	CO, FL, MA, NC

CHAPTER SIX

LITERATURE REVIEW: APPLICATIONS—BOUND

ASPHALT CEMENT AND CONCRETE

Some asphalt concrete mixes with nonferrous slags were reported to exhibit moisture sensitivity, which may need to be addressed with lime treatment of the surface. These slags when used as aggregate are likely to have poor friction properties (TFHRC 2009).

Copper Slag

The Copper Slag Limited company tried copper slag in asphalt concrete and copper oxide blasting grit in California and Georgia to improve asphalt concrete stability (TFHRC 2009). Michigan considered it a direct replacement for coarse and fine aggregate for asphalt concrete, but does not currently use it frequently.

Nickel Slag

Wang and Emery (2004) reported the use of nickel slag for the reconstruction of the Dominican Republic's highway from Santo Domingo to Santiago (about 87 miles in length) from 1994 to 1996. The project used air-cooled nickel slag for fill and granular subbase. The nickel slag passed the expansion, autoclave disruption, and petrographic examination testing.

Nickel slag (TFHRC 2009) is not commonly used in the United States, but it has been experimented with in Ontario, Canada. These mixes showed poor skid resistance, which the article attributes to the smooth, glassy surface. Japan had a better experience with a more porous, rough-textured nickel slag.

Phosphorous Slag

Phosphorous slag (TFHRC 2009) has been used in dense graded HMA in Tennessee, where findings showed that it helped with improving and restoring skid resistance. Montana, Tennessee, and Florida have used air-cooled slags as fine aggregates with reportedly good performance of the mixes.

Zinc Slag

Dunster et al. (2005a) reported the results from a creative workshop (September 16, 2004) that indicated the participants believed nonferrous slags could be used to improve the roadway skid resistance. In particular, zinc slag could be used to improve HMA durability, help reduce the required asphalt binder content, and improve stiffness (i.e., improve rut resistance). The conclusions from the report noted that while these byproducts had a good potential for being used, they were only available in limited quantities.

Dunster et al. (2005b) reported field sections placed with 30% zinc slag showed that the material could be used to produce an acceptable HMA mix (Table 32). The HMA with the zinc slag was manufactured and placed easily using conventional plant and placement equipment; however, the sections with the slag appeared to be richer (i.e., higher in binder content). After 17 months of monitoring, the FWD determined that stiffness was comparable to the control section, and fatigue lives appeared comparable at the short time interval, but the control section had a slightly better resistance to rutting, and with only fair skid resistance.

The Dunster et al. (2005b) research also evaluated the leaching potential of unbound zinc slag. The initial results showed several chemicals above the recommended levels for water quality. These researchers reported that encapsulating the zinc slag with bitumen significantly reduced the leachate concentrations to well within requirements (Table 33).

Zinc slag (TFHRC 2009) has been used in Oklahoma laboratory research, which indicated that the four types of zinc smelter recycled material are potentially suitable for substitution as a fine aggregate. No United States field experience was reported.

PORTLAND CEMENT AND CONCRETE

Copper Slag

Chilean laboratory research by Pavez et al. (2004) evaluated the use of copper slag in mortar cubes with 1:3 cement/slag. The compression tests for the mortar cubes at 3 and 7 days showed that slag mortar had significantly higher compressive strengths than the control samples. The compressive strengths were 4,182 and 1,991 lb/in.^{2} for slag mix and conventional, respectively, at 7 days and 5,177 and 3,257 lb/in.^{2} at 7 days.

TABLE 32
ZINC IN HMA MIXES

Properties	Typical Conventional HMA Properties	HMA with 30% Slag
Binder Content, %	—	4
Indirect Tensile Strength, ksi	345–733	572
Deformation, % strain	<2.0	1.8
Fatigue, life at 200 με	20,000–200,000	30,000
Aging, increase in stiffness, %	<100	32
Indirect Tensile Strength, %	>70%	91

After Dunster et al. 2005b.
50 Pen asphalt cement.
— = data not reported.

TABLE 33
RESULTS FROM TANK LEACHING TEST DATA FROM WWPE (BSEN 1744-3)

Information	Concentration at 336 hours, mg/L			
	Compacted Zinc Slag	Compacted Limestone	Inert Landfill Limits (BSEN 12457-3)	Water Quality Standard
Conductivity, mS/cm	46	109	—	—
pH	6.71	7.44	—	—
As	0.01	<0.12	0.5	0.01
B	<0.056	<0.14	—	1
Cd	0.0012	<0.03	0.04	0.003
Cu	0.001	<0.02	2	—
Pb	0.074	<0.07	0.5	0.25
Hg	<0.001	—	0.01	0.001
Ni	0.001	<0.04	0.40	0.02
Se	0.001	—	0.1	0.01
SO_4	<300	12.22	1,000	250
Zn	0.08	0.06	4	5

— = data not reported.

Lead Slag

A Belgium lab study by Saikia et al. (2008) compared three byproducts: lead slag, municipal solid waste bottom ash, and boiler/fly ash from a fluidized bed combustor (incinerator). The lead slag mixes showed similar compressive strength results, whereas there were some problems with low strengths noted with the municipal solid waste and fluidized bed combustion byproducts. Encapsulating the byproducts in mortars reduced, but did not eliminate, contaminates in leaching tests.

Zinc Slag

Dunster et al. (2005b) conducted field evaluations of rigid pavement sections prepared with and without zinc slag. Typical United Kingdom specifications require air entrainment and water reducing additives to improve the workability of the mix. The laboratory testing of cement with admixtures was prepared with a range of zinc slag: 0%, 50%, 75% portland cement replacement. The researchers noted that the mortar cubes were fragile and tended to crumble around the edges at 75% slag.

Field construction included six 164-ft-long sections: three control and three with zinc slag (50%). Mixing was done at a ready-mix plant and a curing membrane applied with joints saw cut by 24 hours. Extra water had to be added to slag mixes at the site to achieve workability. Traffic was allowed on sections after 28 days of curing. The 7-day requirement for compressive strength was greater than or equal to 5,076 lb/in.^{2}; all mixes met requirements. A visual examination initially identified minor shrinkage cracking and 30 months later showed similar performance with all of the slabs in good condition. Cores showed that carbonation depth after 13 and 30 months was about 2 mm. There was some evidence of slight chloride penetration as a result of de-icing during the winter.

Leachate testing was also completed on crushed concrete material so that recyclability issues that may be encountered when recycling the PCC could be determined. Leaching tests for the crushed materials showed that the zinc and arsenic were comparable to control mix and the lead concentrations were higher than for the control. This was attributed to the enhanced solubility of lead under alkaline conditions. The results showed that contaminates were effectively bound in the PCC application even after crushing. It was concluded that the recycled material would be an acceptable reusable material at the end of the roadway life. The researchers considered that this demonstration project showed that using the zinc slag in PCC applications would effectively immobilize hazardous materials.

CHAPTER SEVEN

SUMMARY

LIST OF CANDIDATE BYPRODUCTS

The list of the most commonly researched and used iron slag byproducts included:

- Blast furnace slag
- Ground granulated blast furnace slag
- Air-cooled blast furnace slag.

Other iron slag byproducts include expanded or foamed BFS, pelletized BFS, and vitrified BFS, but little was found in the literature for research or use of these byproducts.

Steel slag byproducts were used much less frequently than the iron slag byproducts. As with iron slag byproducts, the steel slag byproduct material properties depend strongly on the type of furnace and point in the steel making process from which the byproduct is obtained. The steel slag byproducts identified in the literature included:

- Steel furnace slag
- Electric arc furnace slag
- Basic oxygen furnace slag
- Open hearth furnace slag
- Ladle slag.

The generic term, steel slag, was used in a number of the articles in the literature review. When the specific type of steel slag was identified, the EAF byproduct was the one most frequently identified followed by the BOF slag.

Nonferrous slag byproducts historically identified in the literature included:

- Copper slag
- Nickel slag
- Lead slag
- Zinc slag
- Phosphorous slag.

Few highway applications using these nonferrous slags were found in the literature and state agencies reported no use of copper, nickel, lead, and zinc slags. Only one state reported using phosphorous slag; however, six states indicated that they used slag of an unknown type. This could indicate use of a ferrous or nonferrous slag.

TEST PROCEDURES

Most of the test methods identified as used to evaluate nonferrous slag in highway application literature focused on the use of slag in cements, mortars, and portland cement concretes (33 standards; Table 34). Four test methods were AASHTO methods, one ACI, 18 were ASTM standards, five either European or British, one Japanese, and three Canadian. A total of 14 test methods were specifically identified in the literature for characterizing slags used as aggregate replacements; of these, eight were European, five ASTM, and one Texas DOT standards. Six soils methods (one ASTM, five European) and one miscellaneous standard from Europe complete the list of test methods found in the literature.

MATERIALS PREPARATION AND BYPRODUCT QUALITY CONTROL

Table 35 summarizes performance experiences identified by the state agencies. For the most part, states indicated good to excellent performance of portland pozzolana cement highway applications. Only one state indicated it had a poor performance experience with steel slag when used in HMA applications. Comments are included in Appendix A.

MATERIALS HANDLING ISSUES

The following suggestions were identified for the handling and stockpiling of slag byproducts:

- Weather materials in stockpiles; avoid using freshly produced BFS to minimize reactivity of slags.
- Do not use BFS in wet, poorly drained soils or in areas below the water table to avoid contamination of ground water.
- In unbound applications in the construction of large trafficked areas, compact the material and avoid ponding of water.
- Identify when and where stockpiled BFS could contribute to water contamination.
- Have a method statement for storing and handling, and measures for protecting water quality.

The following adjustments may be needed:

- Increased silo storage at plants to handle additional materials.

TABLE 34
SUMMARY OF TEST METHODS USED BY RESEARCHERS TO INVESTIGATE SLAG BYPRODUCTS

Material	Test Method	Title
Aggregates	EN 12620:2002/ACL2004	Aggregates for concrete
	EN 13043	Aggregates for asphalt
	EN 13139	Light weight aggregates
	EN 13242:2002/AC:2004	Aggregates for unbound and hydraulically bound mixtures for use in civil engineering work and road construction
	EN 13383	Armourstone
	EN 1744-1	Tests for chemical properties of aggregates—Part 1 Chemical analysis
	EN 1744-3	Tests for chemical properties of aggregates—Part 3 Leaching of aggregates
	EN 13043 2002/AC:20045	Aggregates for bituminous mixtures and surface treatments for roads, airfields, and other trafficked areas
	Texas DOT 438	Accelerated Polish for Coarse Aggregate
	ASTM C127	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate
	ASTM C128	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
	ASTM C566	Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying
	ASTM D6928	Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus
	ASTM D3319	Standard Practice for Accelerated Polishing of Aggregates Using the British Wheel
PCC	AASHTO C1202	Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
	AASHTO M302	Standard Specification for Ground Granulated Blast Furnace Slag for Use in Concrete and Mortars
	AASHTO T22	Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens
	AASHTO TP60	Coefficient of Thermal Expansion
	ACI 233	Slag Cement in Concrete and Mortar
	ASTM C109	Standard Test Method for Compressive Strength of Hydraulic Cement Mortars [Using 2-in. or (50-mm) Cube Specimens]
	ASTM C1202	Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
	ASTM C1260	Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
	ASTM C143	Standard Test Method for Slump of Hydraulic-Cement Concrete
	ASTM C148	Standard Test Methods for Polariscopic Examination of Glass Containers
	ASTM C157	Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
	ASTM C227	Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
	ASTM C39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
	ASTM C403	Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
PCC	ASTM C469	Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
	ASTM C490	Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete
	ASTM C512	Standard Test Method for Creep of Concrete in Compression
	ASTM C595	Standard Specification for Blended Hydraulic Cements
	ASTM C666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
	ASTM C672	Standard Test Methods for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
	ASTM C78	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
	ASTM C944	Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method
	ASTM C989	Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars
	BS EN 14227-12	Hydraulic bound mixtures—specifications for soil treated by BFS
	BS EN 14227-2	BFS bound mixtures
	BS EN 15167	GGBFS for use in concrete, mortar and grout

(*continued on next page*)

TABLE 34
(*continued*)

Material	Test Method	Title
	CSA A23.1	Concrete Materials and Methods of Concrete Construction/Methods of Test for Concrete
	CSA A3000-04	Cementitious Materials Compendium
	CSA A3001	Cementitious Materials for Use in Concrete
	EN 15167	Ground granulated blast furnace slag for use in concrete, mortar, and grout
	EN 206	Concrete
	JIT 5211	Japan Standard: Standard of Portland blast-furnace slag cement
Soil	ASTM D698	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort [12,400 ft-lbf/ft^3 (600 kN-m/m^3)]
	EN 13283:2003	Unbound mixtures—specification
	EN 13285	Unbound mixtures—specifications
	EN 14227-12	Hydraulic bound mixtures—Specifications—Soil treated by slag
	EN 14227-2	Slag bound mixtures
	prEN 13282	Hydraulic road binders—Composition, specifications, and conformity criteria
Misc.	EN 12945	Fertilizer

- Plant adjustments (e.g., air flow) to account for the different specific gravities.
- Adjustments to the order of addition or rate of addition of individual components.

TRANSFORMATION OF MARGINAL MATERIALS

One application for producing synthetic aggregates was found using GGBFS treated with carbon dioxide at ambient temperatures and pressures to manufacture lightweight aggregates with aggregate impact values of between 14 and 17.

Three methods of treatment for marginal steel slag materials were found. One method used wet grinding of EAF and AOD steel slags to reduce problems with harmful expansive reactions when used with aluminum or galvanized metals. A second approach that improved the strength-related reactivity of EAF slag by remelting and rapidly cooling the steel slag to increase the glass content showed potential for increasing the slag reactivity. The third method combined BOF steel slag with gypsum waste and cement bypass dust to form a binder without the use of cement.

DESIGN ADAPTATIONS

Volumetric mix designs, HMA or PCC, need to consider the different specific gravities of the slag byproducts. In the case of HMA applications, the mat thickness is commonly specified in units of pounds per square yard. When mixes contain byproducts with high specific gravities, the resulting mat thicknesses will be reduced if the unit weights for the project are not adjusted to account for the change in unit weights.

A limit of less than 35% slag was suggested for enhanced QC/QA testing. Below 35% the standard application QC/QA should be sufficient. Above 35% additional preconstruction testing is needed to ensure compatibility (e.g., set times) of the byproducts and other materials in the application. One agency required a preconstruction trial mix program. A second

TABLE 35
AGENCY RESPONSES TO BARRIERS TO FURTHER USE OF SLAG BYPRODUCTS

Question: Comment on *performance* to the use of combustion byproducts in highway applications that have been either overcome or still exist		
Materials Category	Reasons for Performance Comments	States with Performance Responses
Experience	Limited experience	ID
Workability—Good	*PCC:* Slag cement provides excellent workability	FL
Workability—Poor	*HMA*: Steel slag difficult to place and compact	CO
Performance—Good to Excellent	*HMA:* good performance of slag; moisture resistant; ACBFS provides excellent friction; steel slag improves friction numbers; slag has excellent polish-resistance; good wearing course	AL, IL, IN, IA, KY, MA, OH, WI
	PCC: GGBFS as cement substitute (25%); precast beams, deck units, and girders (30% GGBFS); GGBFS at 35 to 70% by wt of cement	AR, CT, DC, DE, FL, IA, KS, TX, VA, VT, WA
Performance—Poor	*HMA:* longitudinal joint raveling; difficult to maintain	CO

implemented a requirement for the development of a contractor self-test program.

CONSTRUCTION ISSUES

Key factors found in the literature included:

- ACBFS and steel slag in unbound applications need to be used in a dry, well-drained area above the water table to prevent ground-water contamination.
- It is important that all stockpiles be located within the environmentally permitted area.
- Good drainage needs to be provided for stockpile areas.
- Good housekeeping is needed to minimize air borne particles.

FAILURES, CAUSES, AND LESSONS LEARNED

The major problem noted by agencies was the loss of skid resistance by specific slags and the enhanced skid resistance when using steel slag byproducts. Contradictory skid resistance experiences were found in both the literature and agency responses.

BARRIERS

Barriers identified in the literature included:

- Slow set times
- Difficulty with construction in cold weather owing to lower heats of hydration
- Lower early strengths
- Expansive reaction issues with some slags
- Scaling problems in PCC applications
- Decreased compactability and workability (steel slag)
- Standard ACI equations for predicting strength gain with time; estimations of flexural strength from compressive strength needs to be adjusted when using slag byproducts.

Barriers identified in the agency survey responses are summarized in Table 36.

COSTS

When permitting is based on environmental considerations, using GGBFS in particular can result in significant CO_2 reduction credits. From the financial stand point, byproducts need to be located close to the project location to provide a cost savings. Suggested distances ranged from less than 20 to 35 miles from the project.

The high specific gravity of steel slag makes it more costly to haul the same volume of material compared with traditional materials. Higher water absorption capacities for some slags increase the demand for asphalt cements and therefore the cost of HMA application products.

The variability in the byproducts requires additional preconstruction and construction QC testing to design and monitor the uniformity of the project. The additional testing will increase both the design and construction costs.

TABLE 36
AGENCY RESPONSES TO BARRIERS TO FURTHER USE OF SLAG BYPRODUCTS

Question: Comment on *barriers* to the use of combustion byproducts in highway applications that have been either overcome or still exist		
Barrier Category	Reasons for Classification as Barrier	States with Barrier Responses
Availability	Limited local availability; source went out of business	FL, HA, KS, KY, SC, TX, WA
Cost	Expensive; higher haul costs for steel slag because of the higher unit weight	HI, KY
Material Properties	Slag doesn't meet upper specific gravity limit of 2.75; undesirable levels of water absorption; deleterious and foreign materials in slags; expansive reactions; water retention; freeze/thaw problems; scaling; PCC too cool in cold weather	KY, OH, PA, OH, SC, TX, VA, VT, WI
Haul Distances	Long distances	PA
Byproduct Consistency	Variable; lack of chemical control; ACBSF changes chemistry	FL, OH
Experience	Limited experience; limited performance information; lack of data	ID, MD, SC
Stockpiling	Little control on contamination of stockpiles at plants; weathering is needed to minimize expansion reactions	PA, SC
Regulations	*EPA*: Copper slags had problems with lead, cadmium; general concerns; chemistry changes with changes in plant lead to run off issues; required use for cleanup of plant sites	IL, KY, OH, PA, SC, UT
Specifications	*HMA:* thickness regulated by weight per area needs to account for different specific gravities *PCC:* increased placement temperature to 60°F from 50°F to compensate for cool mixes	TX, VA

GAPS

Gaps that need to be addressed in future research include:

- Standardized definitions of byproducts
- Spatial location of slag sources and amounts available for highway application
- Mineralogical, chemical, and mechanical properties for each source of slag
- Best practices guidelines for stockpiling, handling, using, and constructing applications with slag
- Training and education programs for state agency staff
- Recyclability of products with slag content
- Threshold values for standard material and application test methods may be adjusted to account for either improvements or problems when using byproducts
- Reliable performance criteria for key material and application characteristics so that performance-based specifications can be used instead of method specifications
- Reasons for different experiences with skid resistance in HMA pavement surfaces when steel slag is used.

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APPENDIX A

Open-Ended Comments from Agency Survey

State	Performance	Barriers
AL	Granulated ground blast furnace slag is routinely used in HMA and PCC. Slag performs well in open-graded friction coarse asphalt concrete mixes and is moisture resistant.	
AR	Structural and paving concrete have performed well when GGBFS used as substitute (up to 25% by weight) for Type I cement.	
AZ	We have not used any of the above products on an ADOT project to my knowledge.	
CO	Steel slag was very difficult to place and compact for the HMA. The longitudinal joint is raveling and difficult to maintain.	Not much slag is produced in Colorado.
CT	We have had success in using GGBFS at 30% in precast beams, deck units, and girders.	
DC	Good performance in PCC	None
DE	Slag has worked well in concrete for several years.	
FL	Florida uses GGBFS at the concrete producer's option. The rates of use are 50% to 70% by weight of cementitious materials. Slag cement provides excellent workability and durability in our concrete. Air-cooled blast furnace slag (BFS) provided exceptional friction when used in Florida.	Slag is not as available as fly ash in Florida, but it is used in several locations. Our specifications allow its use in any location that fly ash is used so the only barrier would be its availability. BFS for HMA turned out to have too much variability in bulk specific gravity and absorption. When liquid asphalt prices rose, the market dried up, and the source went out of business.
HI		Availability, cost
ID	Used as secondary cementitious material	Not enough experience and supply
IL	ACBF slag and steel slag are our best performing friction aggregates. Illinois uses 300,000–500,000 tons per year.	Illinois used to allow the use of copper slag, but we had some issues with lead and cadmium and the Illinois EPA has put a moratorium on it. It is no longer listed as an approved aggregate.
IN	Air-cooled blast furnace slag and steel slag have been used for many years with success in Indiana. Recently we have allowed the use of steel slag in base and intermediate mixtures if expansion requirements are met prior to use.	
IA	GGBFS improves PCC performance. Steel slag improves HMA friction numbers.	GGBFS is formulated into cement.
KS	A good product to enhance concrete	These products are not typically readily available throughout Kansas.
KY	Slag has provided Kentucky with an outstanding polish-resistant aggregate in HMA surface mixtures for many years.	Slag exhibits an undesirable level of asphalt absorption when utilized in HMA. Also, Kentucky specifications require a pay quantity adjustment when the aggregates used in HMA have a combined bulk specific gravity in excess of 2.75. This requirement often applies when steel slag is utilized; therefore, contractors are reluctant to use this material. Availability, cost, and environmental concerns about steel slag also exist in Kentucky.
LA	GGBFS has been used successfully in PCC mixes for a few years.	
MA	Has been used as mitigation no major issues	Has been used as mitigation; no major issues
MD		We need additional study to know more about the environmental characteristics prior to adopting these materials for highway construction.

State	Performance	Barriers
ME	Used to reduce PCC permeability—good performance	
MO	MoDOT has had very good performance from HMA containing steel slag.	Limited supplies in some areas and variability of air-cooled slags. No slag producers currently in the state.
MS	GGBFS is allowed by current MDOT specifications as a cement replacement up to 50%. GGBFS has been used very successfully on large bridge projects.	Same
NE	It is allowed for use in our PCC mixes.	Cold weather set times can be an issue.
NH	We use ground granulated blast slag as a replacement for portland cement.	
NJ	GGBFS is used in PCC for mitigation of ASR and has performed well. It also is used to reduce the permeability of PCC.	
NV		Limited availability in the geographic area
NY	GGBFS considered as equal to fly ash (Class F)	There is frequently a concern about metals in the leachate.
OH	GGBFS has been a good performer but does appear to have some scaling problems in concrete that don't appear as frequently with fly ash. The ASTM specifications for GGBF are better controlled than fly ash. ACBFS used as aggregate has in portland concrete has generally performed well. ACBFS in asphalt has been a very good wearing surface with little aggregate polishing due to its shape and hardness. We do have some problems with environmental run-off with ACBFS used in aggregate applications because some of the chemical components are not totally stable.	Steel mills see it as a byproduct and only care about controlling the steel not the chemical makeup of the slag. Processers of the ACBFS, at times don't look at the changing chemical makeup and then process the material to assure possible environmental issues don't happen so the owner (state) often ends up with the environmental run-off issues. By processes need to be established to protect against all environmental side issues with ACBFS.
PA	Some slags have retained water in subbase applications under pavements and froze and heaved. Cause was tied to some slags and absorptions, not gradation.	High (water) absorptions and higher unit weights with slags, and these affect too many applications and hauling of these materials. Expansion of steel slags, which limit its use. Deleterious and foreign materials in slags from many years of steel production and stockpiling with minimal regard to keeping stockpiles clean of foreign materials.
SC	The use of GGBFS is allowed by our specifications in PCC but is not widely available in our area.	Supply, environmental concerns, handling (expansion issues require curing in a stockpile and testing); lack of data on long-term performance
TX	Texas experience with performance of ground granulated blast furnace slag in hydraulic cement concrete has been quite positive. One of the 8 mix design options in our standard specification for hydraulic cement concrete allows 35%–50% replacement of the cement with GGBFS.	Supply is limited. Placement of hydraulic cement concrete containing GGBFS in lieu of some of the cement in colder temperatures has had issues. This barrier has been overcome by raising the minimum placement temperature for concrete with GGBFS to 60°F from 50°F.
UT		UDOT is likely to encourage the use of BFS and OHS with the cleanup of the Geneva Steel Site. Otherwise, UDOT does not typically encourage or discourage the use of materials, but instead uses performance-based specs.
VA	VDOT has had good success with a majority of the slag products checked above.	Weight of steel slag (electric arc steel slag) when used in HMA. The specific gravity of EA slag is 3.1–3.15. The specific gravity of normal aggregate is 2.5–2.7. HMA is surface placed at a lb/sy rate. The typical application rate is 11 lb/sy/in thickness. Due to the difference in specific gravity, a conversion factor has to be developed.
VT	Contribute to concrete quality, infrequently we have had apparent scaling issues on sidewalks	
WI	Favorable frictional properties; stable.	Hydration of the product leads to expansion.
WA	GGBFS has performed well.	For us in the Pacific Northwest the greatest barrier is lack of refineries producing these products. No metal smelting = little raw product.

Abbreviations used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation