SLAG—IRON AND STEEL

By Cheryl Cvetic Solomon

Ms. Solomon, a physical scientist with 5 years U.S. Bureau of Mines experience, has been the commodity specialist for iron and steel slag since 1990. Domestic survey data were prepared by Barbara McNair, mineral data assistant.

Iron and steel slags are byproducts of the iron and steel industry and provide an important source of raw materials for construction and road building. Slags are used in road bases, asphalt concrete aggregates, concrete aggregates and products, glass manufacture, mineral wool, railroad ballast, sewage treatment, and soil conditioning.

In 1990, the Federal Environmental Protection Agency (EPA) permanently retained iron and steel slags in the Bevill amendment, or mining waste exclusion, under the Resource Conservation and Recovery Act (RCRA). Iron and steel slags are, therefore, not subject to Federal regulation as hazardous wastes.

Research during the year emphasized the use of granulated slag, particularly in cement. The Australasian Slag Association was formed in Sydney, Australia, to expand the already considerable use of slag in the Australian and Asian markets.

Domestic consumption of iron slag showed a moderate increase when compared with that of 1989, while the consumption of steel slag stayed at the increased level that it had reached in 1989.

DOMESTIC DATA COVERAGE

Data for sales, use, and transportation of iron and steel slag are developed by the U.S. Bureau of Mines from a voluntary survey of U.S. processors. Of the 99 operations canvassed, 99 responded, representing 100% of the total sales or use quantity data shown in table 1. Value data had to be estimated for several operations using reports from prior years adjusted by industry trends.

BACKGROUND

Definitions, Grades, and Specifications

Slags are produced in many metallurgical operations, but this publication deals exclusively with iron slag and steel slag, produced during the ironmaking and steelmaking processes. Slag quantities are given in short tons except where otherwise indicated.

In the production of iron, the blast furnace is charged with iron ore, flux stone (limestone and/or dolomite), and coke for fuel. Two products are obtained from the furnace: molten iron and slag. The slag consists primarily of the silica and alumina from the original iron ore combined with calcium and magnesium oxides from the flux stone. It comes from the furnace as a liquid at temperatures of about 2,700° F, resembling a molten lava.

The blast furnace operation is a continuous process. The raw materials are fed into the top, and the products, molten iron and liquid slag, are drawn off at regular intervals throughout the entire day. The slag is usually run into iron ladles for conveyance to the cooling pit, or it may run straight into a cooling pit close to the furnace.

The density and porosity of the slag are affected by the conditions of cooling as well as by its chemical composition. Depending upon the manner in which the molten slag is cooled and solidified, three distinct types of blast furnace slag can be produced: air-cooled, expanded, and granulated.

Air-cooled slag is allowed to run into a pit adjacent to the furnace or is transported in large ladles and poured into a pit some distance away. Solidification takes place under the prevailing atmospheric conditions, after which cooling may be accelerated by water sprays on the solidified mass. After a pit has been filled and cooled sufficiently to be handled, the slag is dug, crushed, and screened to desired aggregate sizes.

Expanded slag is formed by controlled processing of molten blast furnace slag with water, or with water and other agents such as steam or compressed air, or both. The formation of gases and steam increases the cellular or vesicular nature of the slag, producing a lightweight product. Several methods of expanding the slag are employed involving the pouring of molten slag in open pits or the use of mechanical devices, one of which produces particles in pellet form. Expanded slag is a strong lightweight aggregate suitable for making lightweight concrete, either as building blocks or as structural elements for buildings, or for bridge decks, for example.

Granulated slag is produced when molten slag is cooled rapidly by means of high-pressure water jets, and it solidifies into a glassy, granular product. This is the most rapid cooling process, producing little or no crystallization. The granulated slag may be crushed and screened or pulverized for various applications.

When added to cement, granulated slag enhances the properties of ordinary cement. For example, it will increase the resultant concrete's durability in a marine environment, where concrete is subjected to sulfate attack.

The steel industry also produces steel slag during the steelmaking process. The manufacture of steel involves the removal from the iron of excess quantities of carbon and silicon by oxidation. Steel slag is composed of roughly 50% lime. The other two main constituents are silica and iron oxide. Different types of steel slag are generated from the open hearth, basic oxygen, and electric arc furnaces.

Owing to skid resistant properties of both blast furnace and steel furnace slag, many State agencies or State departments of transportation have specified slag for use in any asphalt surface application having a high volume of traffic. The State of Illinois specifies the use of either blast furnace or steel furnace slag for road construction.[1] In the Greater Chicago area, the use of steel furnace slag is presently specified in these applications. The State of Indiana presently specifies that at least 50% of the coarse aggregate portion of the asphalt mix be blast furnace slag.[2]

Industry Structure

In general, most slag processors operate under contracts of 3 to 10 years with steel companies. The services the slag processors typically offer to the steel mill industry are hauling and transport of the slag away from the mill site, processing of the slag, and recovery and distribution of metallics and nonmetallics. Because slag hauling and processing facilities are capital intensive, the slag processors usually try to negotiate a long-term initial contract with the steel company to recover the capital investment. Subsequent contracts may be shorter.

Depending upon the specific situation at the mill site, the slag processor may assume ownership of the slag at the point of discharge or process for a fee and/or market the finished product and pay royalties to the steel company on sales. Some steel companies may allow the processor to share in royalties on these sales. Although there are many variations in the way a particular slag processor and steel mill will set up their agreement, two possible options are considered here. The slag company may be paid to haul and transport the slag, process it, and market the finished product. The steel company, in turn, receives a royalty on the completed sale and a purchase discount on material recycled to the mill. Secondly, in a minority of the contracts, the slag processor takes ownership of the material and pays little or no royalties to the mill. In this situation, the slag processor would be assuming 100% of the site development and capital costs, including facilities for screening, metallic separation, and crushing and heavy equipment, such as slag pot haulers, to move the material around.

Technology

The slag pelletizer was developed by National Slag Ltd. in Hamilton, Ontario, as a means of bringing very high gas emission levels typical of the "pit foaming" process under control.[3] Pelletized slag is produced by expanding molten blast furnace slag under water sprays and then passing the flow of this pyroplastic material over a spinning drum on which fins are mounted. The fins break up the slag, which then forms into pellets owing to surface tension. While previous expanding processes have been of the batch type, this is a continuous process so that gaseous emissions are effectively diluted by generation over a long period of time. Because of this rapid cooling, the pelletizer can be thought of as an "air granulator."

National Slag Ltd. now has licensed the process in many countries, including Australia, England, France, Japan, Sweden, and the United States. Currently, in Canada, about 400,000 metric tons of slag is pelletized annually and separately ground for use as a cementing material by the St. Lawrence Cement Co., Lafarge Canada Inc., and St. Mary's Cement. The pelletizers are installed near Hamilton, Ontario, where the major steel producers are.

Operating Factors

Until recently, in Canada and the United States, portland cement was relatively cheap, and there was no incentive for the ready-mixed concrete industry to use alternative cementing materials.[4] Environmental concerns combined with high energy costs have forced cement companies to seek alternative cementing materials that can partially replace portland cement in concrete. In the construction industry, the search for less expensive types of binders has led to the utilization of ground granulated blast furnace slag, among other byproducts, to partially replace high energy consuming portland cement in concrete.

ANNUAL REVIEW

Legislation and Government Programs

On January 23, 1990, the EPA published its final ruling concerning retaining iron and steel slags permanently under the Bevill exclusion of RCRA until the EPA completed a required report to Congress and made a regulatory determination.[5] As in the September, 25, 1989, proposal, the Agency evaluated the 20 mineral processing wastestreams by applying the high-volume and low-hazard criteria using a multistep process. The first step entailed applying the high-volume criteria to the available waste generation data. Mineral processing wastes generated above the volume criteria thresholds (an average rate of 45,000 metric tons per facility for nonliquid wastes) passed the high-volume criterion. In the second step, the Agency evaluated each of the 20 wastes with respect to the low-hazard criterion using the relevant waste characteristics. EPA considered a waste to pose a low hazard only if the waste passed both a toxicity test (Method 1312) and a pH test. Finally, the results of the first two steps were consolidated.

In July 1990, the EPA released its Report to Congress on Special Wastes From Mineral Processing (RTC).[6] RCRA required the EPA Administrator to determine whether regulation of iron and steel slags as hazardous wastes under subtitle C, along with 19 other mineral processing wastes, was warranted. This was to be done within 6 months after publication of the report. The Agency accepted public comments until October 1990. These were to be used in the final regulatory determination. No comments were received opposing the RTC recommendation that regulation under subtitle C for those wastes is inappropriate, and the EPA was expected to conclude in 1991 that regulation under RCRA subtitle C is unwarranted for iron and steel slag wastes.

Production

American Aggregates, of Dayton, OH, a building material company with sand and gravel, limestone, and slag operations in the Michigan, Indiana, and Ohio area was acquired in February 1990 by CSR Australia. CSR Australia is a leading Australian building and construction materials company with operations in Australia, New Zealand, North America, and Europe. Construction materials include aggregates, sand, cement, premixed concrete, and asphalt.

C.J. Langenfelder & Son Inc., a general contracting company based in Baltimore, MD, acquired the Maryland Slag Co. from the Arundel Corp. in September 1990. Langenfelder is involved in site and civil work, such as construction, roads, tunnels, and landfill. Arundel Corp. was to market the blast furnace slag products for Langenfelder.

Harsco Corp., of Camp Hill, PA, established a wholly owned subsidiary company to process slag and reclaim metal in Yugoslavia through its Heckett Div., based in Butler, PA. (See Yugoslavia in the World Review section of this report.)

In 1990, Koch Minerals Co., a division of Koch Industries of Wichita, KS, began the construction of a granulation facility to process all slag production from the Weirton Steel No. 1 blast furnace in Weirton, WV. Work was also begun on a facility to grind these granules into cement. Koch's grinding and granulation plant was to begin operations in 1991.

Koch Minerals was also contracted by USX to process slag at the USX Gary, IN, works in 1990. This included air-cooled and expanded slag from five furnaces. In addition, Koch signed an agreement to install a granulation plant at the USX No. 13 blast furnace and then to process the slag granules into cement. Koch planned to start up the granulation and grinding facilities by late 1991.

The Levy Co. of Portage, IN, was involved in many projects utilizing slag. Levy used 67,000 short tons of blast furnace slag to construct a breakwater for the Hammond Marina, Hammond, IN. Levy also completed construction of the Beta Steel slab finishing plant, in Portage, IN, in proximity to Bethlehem Steel. The project employed 40,000 cubic yards of concrete aggregate, 90% of which was pumped.

The Standard Slag Co., Eastern Div., based in Coraopolis, PA, supplied more than one-half million tons of slag for the new Greater Pittsburgh International Airport. Standard was using air-cooled slag coarse aggregate extensively to construct the airport. Slag was being used in runways, taxiways, bridges, and tunnels for the new landside and airside terminals. The entire project is expected to be completed by 1992.

Standard Slag also built a new plant at Browns Reserve in West Mifflin, PA, a slag bank where there is in excess of 16 million tons of blast furnace slag. It is estimated that 700 to 800 thousand tons of slag per year will be obtained from this reserve to keep up with the demand for slag. The slag was produced during the time period of the mid-1920's to the mid-1960's.

Based on American Iron and Steel Institute data, domestic production of iron and steel slag remained essentially unchanged. Sales and consumption of iron and steel slag, however, increased moderately when compared with the level of the previous year. The value of blast furnace slag increased compared with that of 1989, reflecting its use as a substitute for natural aggregates, which in certain geographic locations may be in short supply.

Consumption and Uses

Commercial use of slag reduces cost and landfill requirements for the iron and steel industry. Slag, in its use as a synthetic mineral fiber, has a unique cost-performance relationship that makes it a preferred raw material in industrial applications and as a building material.

Sales of slag products generally reflect demand from the construction industry. The Department of Commerce reported that value of new construction in 1990 declined slightly (2% decline estimated) compared with that of 1989.[7] The value of highway and street construction increased from 1989 to 1990.

Air-cooled blast furnace slag continues to be the predominant form of iron slag processed in the United States, accounting for more than 90% of blast furnace slag sales in 1990. The most significant increase in 1990 in end use for air-cooled slag was as concrete aggregate. Air-cooled blast furnace slag is used in road base, asphaltic concrete aggregate, fill, mineral wool, and glass manufacture. (See table 5 for related data). Mineral wool is used in ceiling tile in commercial and residential buildings and in various thermal and acoustical insulation applications.[8] Mineral wool exhibits low thermal shrinkage and high melting point, which makes it ideal as a fire-resistant material.

Granulated and expanded blast furnace slag accounted for the remainder of the iron slag that was sold or consumed in the United States. Consumption of combined expanded and granulated slag decreased by 15% from that of 1989 to 1,450,000 tons valued at $26,448,000. Granulated slag was predominantly used in the manufacture of cement and expanded slag in the manufacture of lightweight concrete blocks.

Reported steel slag consumption increased slightly compared with that of 1989 (see table 6). It is reported by some slag companies that 90% of steel slag produced is being used. Steel slag used in asphaltic concrete and concrete aggregate increased moderately from that of 1989.

TABLE 1

IRON AND STEEL SLAGS SOLD OR USED[1] IN THE UNITED STATES

(Thousand short tons and thousand dollars)

Year	Blast furnace slag						Steel slag		Total slag[3]	
	Air-cooled		Expanded[2]		Total iron slag[3]					
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
1986	13,501	58,899	1,879	33,851	15,380	92,750	5,689	17,883	21,068	110,633
1987	14,447	65,943	1,774	33,750	16,221	99,693	5,013	15,787	21,234	115,480
1988	14,242	69,415	1,658	32,139	15,900	101,554	5,714	18,058	21,614	119,614
1989	13,783	66,574	1,706	29,143	15,489	95,717	7,376	24,056	22,865	119,772
1990	15,147	77,863	1,450	26,448	16,597	104,311	7,552	22,268	24,149	126,578

[1]Value based on selling price at plant. Includes estimated value data for several operations.
[2]Includes granulated to avoid disclosing company proprietary data.
[3]Data may not add to totals shown because of independent rounding.

TABLE 2

BLAST FURNACE SLAGS SOLD OR USED IN THE UNITED STATES, BY REGION AND STATE

(Thousand short tons and thousand dollars)

Region and State	1989				1990			
	Air-cooled, screened and unscreened		Total, all types		Air-cooled, screened and unscreened		Total, all types	
	Quantity	Value[1]	Quantity	Value[1]	Quantity	Value[1]	Quantity	Value[1]
North Central:								
Illinois, Indiana, Michigan	W	W	W	W	W		W	W
Ohio	2,818	15,728	W	W	W	W	W	W
Total	W	W	8,819	41,572	9,413	44,733	10,006	48,882
Middle Atlantic:								
Maryland, New York, West Virginia	1,351	7,234	W	W	W	W	W	W
Pennsylvania	2,591	14,999	W	W	2,691	17,991	2,891	20,628
Total[2]	3,942	22,323	W	W	W	W	W	W
Undistributed[2]	7,023	28,523	6,670	54,145	3,043	15,139	3,701	34,802
Grand total[3]	13,783	66,574	15,489	95,717	15,147	77,863	16,597	104,311

W Withheld to avoid disclosing company proprietary data; included in "Total and Undistributed."
[1]Value based on selling price at plant.
[2]Includes Alabama, California, Colorado, Kentucky, Texas, Utah, and that indicated by symbol "W."
[3]Data may not add to totals shown because of independent rounding.

Transportation

Most slag is used within about a 30-mile radius of its source. Transportation costs make slag uncompetitive with natural aggregates when transportation distances exceed about 30 miles. Some slag may be delivered over greater distances to areas that do not have other natural aggregates for use in construction and roadbuilding.

Of all the iron and steel slag products sold in 1990, 87% traveled by truck, with an average marketing range of 30 miles; 5% traveled by waterway, with an average range of 251 miles; and 3% traveled by rail, with an average range of 176 miles. The remaining 5% was used at the plant where it was processed (see table 4).

Markets and Prices

The average price, f.o.b. plant, for all iron blast furnace slag was about $6.28 per ton, a slight increase over that of 1989 (see table 7). The price of air-cooled blast furnace slag increased from $4.83 to $5.14 per ton in 1990. Granulated and expanded slag price information was withheld to avoid disclosing company proprietary data. The unit value for steel slag decreased by 10% from that of 1989 to $2.95 per ton.

Foreign Trade

Statistics developed by the U.S. Department of Commerce, Bureau of the Census, indicated that approximately 148,026 tons of granulated blast furnace slag was imported into the country during 1990. The breakdown was as follows: 137,006 tons from Belgium valued at $1,243,002, 11,000 tons from Australia valued at $89,622, and 20 tons from France valued at $5,662. Japanese imports also reportedly entered into the country through the Port of Los Angeles, CA, and 100,000 tons of Canadian imports reportedly entered into the country primarily through Detroit, MI, Cleveland, OH, and Baltimore, MD. The Canadian imports may be, in fact, expanded or pelletized slag.

World Review

Australia.—The Australasian Slag Association, based in New South Wales, Australia, was formed in 1990 by a group of leading steel, cement, quarrying, and slag processing companies in Australia, Japan, New Zealand, Singapore, and the United Kingdom. The slag industry in Australia processes and markets approximately 4 million tons of slag per year. The association's goal is to increase public awareness of the properties and value of slag products and thus to widen the use of slag.

Blue Circle Southern Cement of Sydney, Australia, grinds slag produced by Australian Steel Mill Services in ball mills for use in cement. Blue Circle used the blast furnace slag in the Sydney Harbour Tunnel to improve cement properties in the concrete subject to sulfate attack. Sydney Harbour Tunnel's submerged concrete tunnel segments were built in 1990. The segments contain approximately 200,000 tons of high-quality, sulfate-resistant concrete, made possible by the addition of blast furnace slag. Installation of the sections was planned for Sydney Harbour in 1991.

BHP Steel in Newcastle, Australia, contracted with Steelstone Pty. Ltd. to process and remove basic oxygen furnace slag for the next 10 years. Steelstone was first to recover metallics for recycling in steelmaking and the sinter plant and then to produce and market road construction aggregate. Steelstone is a joint venture of South Coast Equipment Pty. Ltd. of Port Kembla and the Slag Reduction Co. (SRC) of Rotherham, both of which specialize in steel mill services. Although the use of basic oxygen furnace slag as a roadmaking material is new to Australia, SRC has been turning processed and graded steel slag into coated roadstone

TABLE 3

PROCESSORS OF IRON AND STEEL SLAG IN THE UNITED STATES IN 1990

Company	Plant location	Slag source: Iron: Blast furnace	Slag source: Steel: Basic oxygen furnace	Slag source: Steel: Open hearth	Slag source: Steel: Electric arc furnace	Blast furnace slag type
Alexander Mill Services	Prospect, PA				X	—
American Aggregates	New Miami, OH	X				Air-cooled.
Do.	Middletown, OH	X				Do.
Blue-Circle Atlantic Inc.	Sparrows Point, MD	X				Granulated.
Buffalo Crushed Stone	Buffalo, NY	X				Air-cooled.
Dunbar Slag Co. Inc.	Wheatland, PA	X	X	X		Do.
Fountain Sand and Gravel Co.	Pueblo, CO	X				Do.
Fritz Enterprises Inc.	Lorain, OH	X				Do.
Gascola Slag Co.	Penn Hills, PA			X		—
Heckett Co.	Emeryville, CA				X	—
Do.	Fontana, CA		X			—
Do.	Bourbonnais, IL				X	—
Do.	Chicago, IL	X				Air-cooled and expanded.
Do.	Sterling, IL				X	—
Do.	Indiana Harbor, IN		X			—
Do.	Ashland, KY	X	X			Air-cooled.
Do.	Coalton, KY				X	—
Do.	Newport, KY				X	—
Do.	Owensboro, KY				X	—
Do.	Kansas, MO				X	—
Do.	Jackson, MS				X	—
Do.	Charlotte, NC				X	—
Do.	Canton, OH				X	—
Do.	Mansfield, OH				X	—
Do.	Warren, OH		X		X	—
Do.	Butler, PA				X	—
Do.	Fairless Hills, PA			X		—
Do.	Johnstown, PA				X	—
Do.	Natrona Heights, PA				X	—
Do.	Georgetown, SC				X	—
Do.	Geneva, UT	X		X		Air-cooled.
Do.	Kent, WA				X	—
Do.	Seattle, WA				X	—
Hempt Bros. Inc.	Steelton, PA			X		—
International Mill Service	Fort Smith, AK				X	—
Do.	Pueblo, CO		X		—	
Do.	Claymont, DE				X	—
Do.	Tampa, FL				X	—
Do.	Atlanta, GA				X	—
Do.	Cartersville, GA				X	—
Do.	Alton, IL				X	—
Do.	Chicago, IL	X	X		X	Air-cooled.
Do.	Granite City, IL		X			—
Do.	Huntington, IN				X	—
Do.	Laplace, LA				X	—
Do.	Baltimore, MD				X	—
Do.	Jackson, MI				X	—
Do.	Monroe, MI				X	—
Do.	St. Paul, MN				X	—

TABLE 3--Continued

PROCESSORS OF IRON AND STEEL SLAG IN THE UNITED STATES IN 1990

Company	Plant location	Slag source: Iron: Blast furnace	Slag source: Steel: Basic oxygen furnace	Slag source: Steel: Open hearth	Slag source: Steel: Electric arc furnace	Blast furnace slag type
International Mill Service—Continued	Kansas City, MO				X	—
Do.	Perth Amboy, NJ				X	—
Do.	Newport, MN				X	—
Do.	St. Paul, MN				X	—
Do.	Riverton, NJ				X	—
Do.	Marion, OH				X	—
Do.	Middletown, OH		X			—
Do.	Mingo Junction, OH		X			—
Do.	Sand Springs, OK				X	—
Do.	Beaver Falls, PA				X	—
Do.	Burgettstown, PA				X	—
Do.	Coatesville, PA				X	—
Do.	Midland, PA				X	—
Do.	Pricedale, PA		X		X	—
Do.	Reading, PA				X	—
Do.	Jackson, TN				X	—
Do.	Beaumont, TX				X	—
Do.	El Paso, TX				X	—
Do.	Jewett, TX				X	—
Do.	Longview, TX				X	—
Do.	Midlothian, TX				X	—
Do.	Plymouth, UT				X	—
Do.	Weirton, WV		X			—
C. J. Langenfelder & Son Inc.	Sparrows Point, MD		X			—
Do.	Braddock, PA		X			—
Edward C. Levy Co.	Detroit, MI	X	X		X	Air-cooled and expanded.
The Levy Co. Inc.	Burns Harbor, IN	X	X		X	Do.
Do.	East Chicago, IN	X				Air-cooled.
Do.	Gary, IN			X		—
Maryland Slag Co.	Baltimore, MD	X				Air-cooled.
Koch Minerals	Gary, IN	X				Air-cooled and expanded.
Sheridan Corp.	Lebanon, PA	X				Do.
The Standard Slag Co.	Granite City, IL	X				Air-cooled.
Do.	Cleveland, OH	X				Do.
Do.	Lordstown, OH	X				Granulated.
Do.	McDonald, OH	X				Air-cooled.
Do.	Mingo Junction, OH	X				Do.
Do.	Warren, OH	X				Do.
Do.	Weirton, WV	X				Do.
Do.	West Mifflin, PA	X	X	X		Do.
Do.	West Aliquippa, PA	X	X	X		Do.
Do. (Brown Reserve)	West Mifflin, PA	X				Do.
Stein, Inc.	Cleveland, OH		X		X	—
Do.	Lorain, OH		X		X	—
St. Louis Slag Products Co.	Granite City, IL	X				Air-cooled.
Vulcan Materials Co.	Alabama City, AL	X	X			Do.
Do.	Fairfield, AL	X	X			Do.
Warner Co.	Bala-Cynwyd, PA	X				Air-cooled and expanded.
Waylite Corp.	Bethlehem, PA	X				Do.

TABLE 4

SHIPMENTS OF IRON AND STEEL SLAG IN THE UNITED STATES IN 1990, BY METHOD OF TRANSPORTATION

Method of transportation	Quantity (thousand short tons)
Truck	21,127
Waterway	1,189
Rail	701
Not transported (used at plant site)	1,132
Total	24,149

since the 1930's. BHP began work on the slag utilization project in 1986. Between 200,000 and 250,000 tons of slag produced annually at the steelworks was expected to be absorbed by the process.

Steel Cement Ltd. was formed in 1989 by Independent Cement & Lime Pty. Ltd. (45%), Ube Industries Ltd. (26%), Adelaide Brighton Cement Investments Ltd. (20%), and AICIA Pty. Ltd. (9%) with the intent of using Australian granulated blast furnace slag in cement production and other areas. In 1990, Steel Cement shipped 11,000 tons of the granulated blast furnace slag to Hawaii to be used as fertilizer for cane fields as its first export.

South Africa, Republic of.—Iscor granulated 152,000 tons of slag at Pretoria Works for use in cement, 548,000 tons at Vandervijlpark (63% for cement), and 576,000 tons at Newcastle (37% for cement). The Republic of South Africa experienced a severe depression in the construction and mining industries in 1990 and did not use all of its available capacity for granulating slag. Iscor's steel slag production in Pretoria was 142,000 tons in Vanderbijlpark and 190,000 tons in Newcastle. The concept of utilizing blast furnace slag to produce cementitious material was first researched in the Republic of South Africa in the 1950's. After successful trials on Iscor slags, Building Binders Ltd. was formed to exploit this technology, and a plant was built in 1955 at Vanderbijlpark adjacent to the Iscor works. The business progressed rapidly and, in 1962, the three major South African cement companies—Pretoria Portland Cement, Blue Circle, and Anglo Alpha—acquired the shares of the company, and the name was changed to Slagment Ltd. Based on the success of this venture, a second plant was

TABLE 5

AIR-COOLED BLAST FURNACE SLAG SOLD OR USED IN THE UNITED STATES, BY USE[1]

(Thousand short tons and thousand dollars)

Use	1989		1990	
	Quantity	Value	Quantity	Value
Asphaltic concrete aggregate	1,673	8,771	2,136	12,049
Concrete aggregate	1,394	8,043	1,780	10,405
Concrete products	412	2,586	474	2,557
Fill	1,651	5,119	1,558	5,844
Glass manufacture	W	W	W	W
Mineral wool	510	3,285	581	3,614
Railroad ballast	248	1,285	397	2,024
Road base	7,276	32,981	7,667	36,827
Roofing, built-up and shingles	92	1,027	78	726
Sewage treatment	W	W	W	W
Soil conditioning	W	W	W	W
Other[2]	527	3,474	494	3,817
Total[3]	13,783	66,574	15,147	77,863

W Withheld to avoid disclosing company proprietary data; Included with "Other."
[1]Value based on selling price at plant.
[2]Includes ice control, miscellaneous, and uses indicated by symbol W.
[3]Data may not add to totals shown because of independent rounding.

TABLE 6

STEEL SLAG SOLD OR USED IN THE UNITED STATES, BY USE[1]

(Thousand short tons and thousand dollars)

Use	1989		1990	
	Quantity	Value	Quantity	Value
Asphaltic concrete aggregate	969	3,835	1,066	3,153
Fill	1,374	5,057	1,005	3,510
Railroad ballast	213	670	227	621
Road bases	3,141	9,169	3,182	8,901
Other[2]	1,679	5,325	2,071	6,081
Total[3]	7,376	24,056	7,552	22,268

[1]Excludes tonnage returned to furnace for charge material. Value based on selling price at plant.
[2]Includes ice control, soil conditioning, and miscellaneous uses.
[3]Data may not add to totals shown because of independent rounding.

TABLE 7

AVERAGE VALUE PER TON AT THE PLANT FOR IRON AND STEEL SLAG SOLD OR USED IN THE UNITED STATES, BY TYPE

Year	Iron blast furnace slag				Steel slag	Total slag
	Air-cooled	Granulated	Expanded	Total iron slag		
1986	$4.36	W	$12.57	$6.03	$3.14	$5.25
1987	4.56	W	W	6.15	3.15	5.42
1988	4.87	W	W	6.39	3.16	5.48
1989	4.83	W	W	6.18	3.26	5.24
1990	5.14	W	W	6.28	2.95	5.24

W Withheld to avoid disclosing company proprietary data.

TABLE 8

AVERAGE SELLING PRICE AND RANGE OF SELLING PRICES AT THE PLANT FOR IRON AND STEEL SLAG IN THE UNITED STATES IN 1990, BY USE

(Dollars per short ton)

Use	Iron blast furnace slag						Steel slag	
	Air-cooled		Granulated		Expanded			
	Average	Range	Average	Range	Average	Range	Average	Range
Asphalt concrete aggregate	5.64	2.44-10.00	—	—	—	—	2.96	0.46- 4.75
Cement manufacture	W	W	W	W	—	—	—	—
Concrete aggregate	5.85	2.50-10.00	—	—	—	—	—	—
Concrete products	5.39	3.90-10.00	—	—	—	—	—	—
Fill	3.75	1.46- 7.25	—	—	—	—	3.49	.15-10.00
Glass manufacture	W	W	—	—	—	—	—	—
Lightweight concrete aggregate	—	—	—	—	W	W	—	—
Mineral wool	6.22	4.41-10.25	—	—	—	—	—	—
Railroad ballast	5.34	3.88- 8.00	—	—	—	—	—	—
Road bases	4.80	2.73- 8.00	W	W	—	—	2.80	.39- 5.72
Roofing, built-up and shingles	9.29	4.00-12.86	—	—	—	—	—	—
Sewage treatment	W	W	—	—	—	—	—	—
Soil conditioning	W	W	W	W	—	—	W	W
Other	4.16	1.93- 7.37	—	—	—	—	2.84	.35- 5.59

W Withheld to avoid disclosing company proprietary data.

built in 1966 at Pretoria. After this, Slagment increased production from the initial 65,000 tons per year to 600,000 tons per year. In 1985, the third plant was built near the Newcastle ironworks, and today the three plants have a production capacity of 1.5 million tons per year of cementitious slag material. The Newcastle plant was subsequently sold to one of Slagment's major customers, Natal Portland Cement, which now manufactures the product under license to Slagment.

U.S.S.R.—Approximately 88% of the slags produced in the U.S.S.R. is utilized. Blast furnace slags amounted to more than 41 million tons. Of that amount, about 25 million tons was granulated, 16 million tons was used as building stone, and 85,000 was used as mineral wool. Steel slags accounted for a little more than 9 million tons. Of these, 375,000 tons is used as slag-lime fertilizer and a little more than 7 million as building stone.[9] Slag was used mainly in the production of cement, concrete, and in slag wool and in road construction and agriculture. According to U.S.S.R. economic indicators, including price, labor, and cost of production, slag industries were profitable.

The Cherepovets works in the U.S.S.R. produces granulated blast furnace slag.[10] The granulating complex processed slag from the Krivorozhstal steelworks. The granulators grind and crush the molten slag, as well as hydraulically transport, dewater, and collect the granulated slag from the blast furnace without the use of cinder cars.

United Kingdom.—Appleby Group, South Umberside, continued to increase its penetration into the cementitious market in spite of the recession in industry. The Group has made major inroads into the concrete, glass, and abrasives markets. Frodingham, the largest company in the Appleby Group, produced ground granulated blast furnace slag for use as a cement extender. It was the first such producer in the United Kingdom.

Appleby has invested in high-pressure roller crushers to increase production. The environmental concerns in the United Kingdom have pushed iron manufacturers toward production of granulated and away from air-cooled blast furnace slag. This trend is likely to continue.

Yugoslavia.—Harsco Corp., of Camp Hill, PA, established a 100%-owned company for metal reclamation and slag processing in Yugoslavia through its Heckett Div. Designated Heckett Yugoslavia Ltd., the new company was one of the first U.S.-funded projects to begin operations in Yugoslavia since the liberalization of foreign investment laws by the Yugoslavian Goverment in 1989. The new company entered into a long-term contract for slag processing and metal recovery at the Metalurski Kombinat Smederevo (MKS) steel plant in Smederevo in the Republic of Serbia near Belgrade.

Current Research

Current research was dominated by that done on granulated blast furnace slag. A study at the Canada Centre for Mineral and Energy Technology (CANMET) of the Energy, Mines and Resources Canada reviewed the use of granulated blast furnace slag in concrete in Canada.[11] Three areas were covered: mixture proportions and properties of fresh concrete incorporating slag, mechanical properties of concrete incorporating slag, and durability of concrete incorporating slag. The mixture proportions of granulated blast furnace slag to be used in concrete depend upon the specific job. As an example, granulated slag would replace 25% to 50% by weight of cement if the goal were to conserve cement in concrete operations. However, if the purpose were to increase concrete durability, such as sulfate resistance, then the slag content would be at least 50% of the total cementitious material. Because each slag has a unique chemical composition, glass content, and fineness, it is necessary to perform exploratory investigations with the cement, aggregates, and chemical admixtures to be used in each specific project.

The mechanical properties of concrete incorporating slag are highlighted by the compressive strength development of slag concrete. Compressive strength development, as well, depends upon the type, fineness, activity index, and the proportions of slag used in concrete mixtures. Other factors that affect the performance of slag in concrete are the water-to-cementitious materials ratio and the type of cement used.

The increased durability of portland cement concrete incorporating slag results primarily from a finer pore structure and reduced contents of easily leached calcium hydroxide in the hardened cement paste. Also, the dilution of the reactive component of the portland cement by the replacement of cement by slag contributes to increased resistance of slag concretes to sulfate attack.

Several studies completed at CANMET in 1990 illustrate the above areas. The amount of slag replacing cement has been limited in the past by the relatively slow strength development of the slag. The studies have shown that, in slag concretes, strength development can be accelerated by the addition of alkali activators such as lime, sodium hydroxide, sodium carbonate, sodium silicate and, in general, salts of weak acids and strong bases. The purpose of the study was to formulate the proportioning of concrete mixtures made with ground-granulated blast furnace slag activated with sodium silicate and to determine their properties and durability.[12] Six concrete mixtures were made using ground-granulated blast furnace slag, sodium silicate, lime, crushed limestone, natural sand, and a hydrocarbon air-entraining admixture. Among the conclusions, it was found that the sodium silicate-to-slag ratio was an important factor affecting the properties of fresh and hardened concrete and that the compressive strengths were comparable to or higher than those of portland cement concrete with equivalent water-to-cement ratio and workability.

In another study at CANMET, mechanical properties of slag, abrasion resistance, and chloride-ion permeability of concrete incorporating ground-granulated blast furnace slag from northern Ontario were investigated.[13] Nine concrete mixtures were made with the water-to-cementitious materials ratio of the mixtures ranging from 0.45 to 0.70. The percentage of slag used as a replacement by mass for the portland cement varied from 0% to 50%. Among other findings, the strength development characteristics of the slag concrete indicated that granulated blast furnace slag can be satisfactorily used as a partial replacement for portland cement in concrete.

Engineers at the Department of Civil Engineering ADFA in Australia investigated the possibility of using slagment (65% cement and 35% slag) instead of plain cement to manufacture structural-grade concretes.[14] The strength development of three grades of plain cement concretes, portland blast furnace slag concretes, and concretes in which 15% and 35% of slagment was replaced by fly ash (ternary blends) were tested. They found that low and medium-strength slagment concretes reaching 20 and 35 megapascals gave higher strength than those cast with plain cement. However, the addition of fly ash to slagment generally decreased concrete strength. In addition, the results suggest that the strength of the slagment concretes are less affected by lack of curing than the strength of the plain cement concretes.

Slag-blended cements have been used to improve the sulfate resistance of concrete in Europe for decades. However, they had not been widely used in North America because slags had limited availability. There were also concerns that not all slags performed equally because of variations in slag composition, reactivity, and fineness from different sources. In addition, until the 1970's in Canada and the United States, portland cement was not expensive, and there was no reason to find substitutes for it. Thus, in Canada in 1976, with higher energy costs renewing interest in slag, a research program was begun at McMaster University to monitor concrete and mortar specimens incorporating Canadian slag. Research continued at Trow Ltd. and then at the University of Toronto, and the results of a 10-year study of slag exposure to sulfate solutions were published.[15] The major finding was that replacement of a 50 percent by mass of normal portland cement by slag provided equivalent or better sulfate resistance than sulfate-resistant portland cement. Sulfate resistance was found to decrease with increasing slag aluminum oxide content and to improve with reduced slag permeability and reduced slag calcium hydroxide content, among other factors. The results of the study are based only on particular pelletized slags ground to a specific fineness.

Researchers at the University of Sherbrooke, Sherbrooke, Quebec, Canada, studied the microstructural development of a very high strength concrete containing 10% silica fume, 30% slag replacement for cement, and a high-range water-reducing admixture.[16] Chemical and mineral additives traditionally have been used to improve the properties of fresh and hardened concrete and to reduce costs by replacing cement with low-cost industrial byproducts. The concrete displayed high early strength and reached 94 MPa at 28 days. Past experience has shown them to be very efficient components in the production of very high strength concrete. The benefits of blended elements incorporating slag for high-strength concrete production have been illustrated during the construction of Nova Scotia Plaza.[17]

Portland cement containing 50% to 80% blast furnace slag has higher resistance to seawater attack and to alkali-silica reactions and a better development of strengths than portland cement. The Laboratory of Metal Engineering and Mineral Geochemistry, Ecole Superieure Energie et Materiaux, Universite d'Orleans, France, investigated the influence of the nature of solid and aqueous solutions on the composition of the hydrated slag.[18] To understand the properties of cement and concrete containing slag powders or sands, the researchers determine the structure, composition, and origin of the hydrated layers grown after different reaction times. Two synthetic glassy slags with high aluminum and magnesium contents were hydrated at 40° C at time periods ranging from 4 hours to 150 days in water and alkaline solutions. Glassy slags in alkali media were more highly reactive than in water.

Researchers at the Regional Research Laboratory in Assam, India, have investigated the activation of low-lime, high-alumina granulated blast furnace slag by anhydrite to prepare supersulfated slag cement.[19] The latent hydraulic property of granulated blast furnace slag is advantageously used in making various cementitious binders by activating it with different activators, such as ordinary portland cement. The hydraulic activity of a slag depends mainly on its glassy phase content and chemical composition. In general, the higher the glassy phase, the lime and alumina contents, the higher is the hydraulic property of the slag. Ordinary portland cement clinker (commercial grade) and slag procured from the Rourkela steel plant were ground separately in a laboratory ball mill. The researchers concluded that the optimum quantity of anhydrite required to make supersulfated slag cement from a low-lime (26%), high-alumina (27%) Indian blast furnace slag is in the range of 15% to 20%. The enhancement of strength characteristics in the latter stages of hydration was attributed to the formation of calcium-silicate hydrates.

The King Fahd University of Petroleum and Minerals has investigated the long-term corrosion-resisting characteristics of concrete incorporating slags or pozzolans.[20] They investigated the corrosion-resisting characteristics of concrete samples made with a blast furnace slag cement, two Class F fly ashes, a natural pozzolan, and a preblended portland-fly ash cement. Specimens were immersed in 5% sodium chloride solution for a period of more than 5 years, and the corrosion activity was evaluated by monitoring the half-cell potentials and measuring the corrosion rate of embedded steel using a linear polarization resistance technique. The investigators concluded that the corrosion rate of steel in concrete made with blast furnace slag cement is lower than in the other concretes tested.

Investigators at the Building Research Station have studied the hydration behavior of refractory aluminous cement and ground-granulated blast furnace slag over a range of temperatures.[21] Commercial high-alumina cements (HAC) show a reduction in compressive strength when kept in a hot and humid atmosphere over a prolonged period of time. It has been claimed that the strength loss suffered by HAC under hot and humid conditions can be counteracted by the addition of sufficient quantities of ground-granulated blast furnace slag to the cement. When kept in hot water over a long period of time, the 1:1 cement plus slag mixture has not shown any reduction in strength. The researchers concluded that there are chemical interactions between the cement and the granulated blast furnace slag that form sulfate hydrates and accompanying gel material. These inhibit the formation of the hydrate phase that is responsible for reduction in strength of HAC concrete.

Ground-granulated blast furnace slag is recognized as giving specific qualities to the composite-cement concrete making it superior to concrete made from portland cement alone. The Department of Mechanical and Process Engineering at the University of Sheffield, England, studied the engineering properties of slag concrete when 50% to 70% by weight of portland cement was replaced by slag.[22] The study emphasized that adequate drying should be an essential specification when slag is incorporated in concrete. Prolonged drying of inadequately cured slag concrete can adversely influence its long-term durability owing to internal microcracking and loss of elastic modulus.

The U.S.S.R. studied the reduction of dust and gas emissions from slag forming mixtures used in continuous casting.[23] Introduction of effective means of recovering waste products was investigated. It was discovered that the basic components of the gas emissions are the flourine and carbon compounds, the quantity of which, depending upon the mixture, composes from 1.8 to 10.4 milligrams per gram of mixture. When using granulated slag, the dust emissions are insignificant.

OUTLOOK

The use of granulated slag is expected to increase owing to environmental and cost considerations. Using granulated slag reduces energy costs that would be higher when using portland cement. As more companies decide to granulate slag, more slag may be used in cement, and less may be available for use as an aggregate in building and construction. Granulated slag production capacity may exceed demand as the amount of slag consumed approaches an upper limit for slag use in cement. On the other hand, in some areas of the country, there may be shortages of blast furnace slag because of blast furnace shutdowns. There may also be shortages in steel slag as a result of an expected downturn in the steel industry in 1991.

The slag industry is expected to pursue markets in traditional areas such as building and road maintenance and resurfacing as well as to seek nontraditional niches. The use of slag and fly ash as a substitute for open graded fill is one such nontraditional area. Slag used in ways other than as replacement for natural aggregates will represent a new area for slag to be used in the future. Slag industry demand, both for cement and aggregate end use, depends upon the construction industry, which in turn depends on general economic conditions.

Events of the past few years have indicated that there continues to be foreign interest in acquiring U.S. slag companies and that the total number of U.S. slag companies may decrease as consolidation occurs. Downstream integration of the industry continues, with increased emphasis in the United States in marketing slag in higher value end uses such as in cement. Iron slag processors are increasingly part of larger companies having captive markets in the aggregate, cement, and construction markets.

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