SLAG—IRON AND STEEL

By Cheryl Solomon

Iron and steel slags are byproducts of the iron and steel industry. They are used not only in construction and roadbuilding, but also in other ways such as in waste stabilization. Slags are used in road bases, various types of concrete aggregates, fill, glass manufacture, mineral wool, railroad ballast, and soil conditioning.

Research during the year emphasized blast furnace slags incorporated into blended cements, and used in oil well drilling, and waste stabilization, as well as various uses of steel slags.

Total slag consumption increased by 6%, partly due to increased demand for slag in the construction industry and increased quantities of slags available. Domestic consumption of reported iron slag stayed the same when compared with that of 1993, while the consumption of reported steel slag increased by 17%.

Legislation and Government Programs

The Environmental Protection Agency proposed a ruling, the Comprehensive Guideline for Procurement of Products Containing Recycling Materials. The guideline designated items that could be made with recovered materials and recommended procurement practices. The guideline incorporated five areas: cement and concrete, paper and paper products, re-refined lubricating oil, retread tires, and building insulation. The proposed action was to foster markets for materials recovered from solid waste by using government purchasing power to stimulate use of these materials in the manufacture of new products. Ground granulated blast furnace slag was included among the recycled products that could be used in cement and concrete for a variety of applications.[1]

Production

Slag was produced in 29 States *(See tables 2 and 3.)* and by 17 companies.

The Edward C. Levy Co., based in Detroit, MI, with slag operations in Australia, Indiana, Michigan, and Ohio, marketed blast furnace and steel furnace slag as well as limestone and sand and gravel in the Midwest, Southeast, and Western States. New ventures included various electric furnace mini-mill operations throughout the United States.

The majority of the Edward C. Levy's blast furnace slag products were used in concrete asphalt highway and roadway paving products with some expanded blast furnace slag used as a lightweight aggregate in masonry block production. The steel furnace slag was used primarily as an aggregate in hot mix asphalt and as a general maintenance base material.

Koch Minerals Co. based in Wichita, KS, was involved in a number of projects involving blast furnace slag. The National Rock and Roll Hall of Fame located in Cleveland, OH, utilized ground granulated blast furnace slag as a replacement for portland cement throughout the structure's concrete. Seventy percent replacement levels were used for the low heat mass portions of the project. A 40% replacement level was used for structural columns, and 30% replacement level was used for project flat work. The Hap Cremean Waste Water Treatment Plant located in Columbus, OH, used concrete to construct holding ponds, treatment tanks, and ancillary structures. The concrete mix design used a 30% ground granulated blast furnace slag replacement of Type I portland cement in lieu of using 100% moderate sulfate resistant Type II portland cement. Koch Minerals also supplied air-cooled slag aggregate for the 6.8 mile four-lane hot mix reconstruction project of Interstate-94 between Michigan City Route 35 and the Michigan State line. One hundred percent slag aggregate was used on this project for pavement base, binder, and surface courses. Natural sand was used for the hot mix fine aggregate fraction. A total of 168,000 metric tons of hot mix aggregate was placed. Approximately 95,000 tons of air-cooled slag aggregate was used.

The Levy Co. of Portage, IN, was involved with efforts to use slag more widely in the States of Illinois and Indiana. The Indiana Dept. of Transportation (INDOT) altered existing base design for concrete pavement with the intent to reduce moisture infiltration through the bottom layer of the dense graded aggregate subbase. As a result of a cooperative research effort between INDOT and the Levy Co., INDOT established a new specification for this application, allowing slag to be utilized under a modified gradation. It was anticipated that INDOT's acceptance of the modified gradation would preserve 50,000 to 100,000 tons of potential slag base business on an annual basis. The Levy Co. received approval from the Illinois Department of Transportation's Greater Chicago District to supply blast furnace slag chips as an alternate to slag furnace slag chips for high volume asphalt surface mixes. The most notable project to utilize the blast furnace chips was the Kennedy Expressway in Chicago, IL, which covered 6 miles of pavement. The $5.5 million reconstruction project required 23,000 tons of blast furnace chips and was completed in 2 months.

Consumption

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 93 operations canvassed, 88 responded, representing 96% of the total sales or use, quantity data shown in table 1. Quantity data were estimated for the remaining operations. Value data had to be estimated for several operations using reports from prior years adjusted by industry trends. (See table 1.)

Sales of slag products generally reflected demand from the construction industry. The Department of Commerce reported that value of new construction in 1994, $507 billion, increased by 9% compared with that of 1993.[2] The value of highway and street construction, $40.19 billion, was estimated to have increased by approximately 8% from that of 1993.

Many of the projects involving slag in 1994 were related to highway repaving projects. Blast furnace slag was used as a ground product to replace portland cement in concrete, as a special lightweight aggregate in blocks and highrise buildings, as a concrete aggregate replacing common concrete aggregates and sands, as a highly skid-resistant asphalt aggregate, and as a road base where the rough, interlocking surface and shape and cementitious properties enhance its load-bearing values.

Air-cooled blast furnace slag was the predominant form of iron slag processed in the United States, accounting for 87% of blast furnace slag sales in 1994. In 1994, 10.7 million tons of air-cooled slag was used with a value of $62.4 million. The most significant end use in 1994 was for air-cooled slag used as a road base. Air-cooled blast furnace slag also was used as an asphaltic concrete aggregate, other concrete aggregate and concrete products, fill, mineral wool, railroad ballast, glass manufacture, and sewage treatment. *(See table 4 for related data.)*

Consumption of combined expanded and granulated slag was 1.6 million tons valued at $51.1 million. Granulated slag was predominantly used in the manufacture of cement and expanded slag in the manufacture of lightweight concrete blocks.

Steel slag was principally used for highly skid-resistant asphalt road surfaces, road bases, and asphaltic aggregates. Reported steel slag consumption increased by almost 17% compared with that of 1993. *(See table 5.)* Steel slag used on road bases, in fill, in asphaltic concrete aggregate, and railroad ballast increased by 19%, 46%, 4.6%, and 38%, respectively.

Transportation

Most slag is used within about a 50 kilometer (km) radius of its source. Trucking costs make slag uncompetitive with mined aggregates when transportation distances exceed about 50 km. Some slag may be delivered over greater distances to areas that do not have other aggregates for use in construction and roadbuilding.

Of all the iron and steel slag products sold in 1994, 85% traveled by truck, with an average marketing range of 45 km; 4% traveled by waterway, with an average range of 404 km; and 4% traveled by rail, with an average range of 400 km. The remaining 7% was used at the plant where it was processed. *(See table 6.)*

Prices

The average price, f.o.b. plant, for all blast furnace slag was approximately $9.23 per ton, almost 10% more than that of 1993. *(See table 7.)* Air-cooled blast furnace slag averaged $5.84 per ton, virtually the same as that in 1993. Granulated and expanded slag price information were withheld to avoid disclosing company proprietary data. The unit value for steel slag was $3.45 per ton, virtually the same as in 1993.

Foreign Trade

Statistics developed by the U.S. Department of Commerce, Bureau of the Census, indicated that approximately 199,000 tons of granulated blast furnace slag was imported during 1994. Seventy-one percent of these imports came from Canada, 15% from the Republic of South Africa, and most of the remainder from Norway. Forty percent of the imports entered through Savannah, GA; 31% through Baltimore, MD; 23% reportedly entered through Cleveland, OH; and the remainder through Buffalo, NY, and Philadephia, PA. The Canadian imports may be expanded or pelletized slag.

Exports of granulated slag were 4,000 tons. Seventy percent of the slag exports went to Canada, 20% to Japan, with the remaining 10% going to 12 other countries.

World Review

Blast furnace slag production in Europe, including Austria, Belgium, Finland, France, Germany, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom increased by approximately 5%. Approximately 26.2 million tons of blast furnace slag was produced. It was estimated that 31% of this was granulated slag. Basic oxygen steel slag production was estimated at 10.1 million tons.

Australia.—Approximately 3 million tons of iron and steel slag was produced, about the same as that in 1993. There were no significant changes in slag production from 1993 at the iron and steel production centers in Australia. About 375,000 tons of blast furnace slags was used in Australian cements, with another 500,000 tons used in road construction and as an aggregate in concrete. Slag production and consumption centered around the iron and steel slag produced by BHP Steel in two areas in Australia—Port Kembla and Newcastle in New South Wales.

The BHP plant at Whyalla, South Australia, also produced 350,000 tons of blast furnace rock slag and 125,000 tons of basic oxygen furnace slag. The plants' isolation from population centers and markets meant that the slag produced was landfilled.

In the Port Kembla area of New South Wales, the slag processor was Australian Steel Mill Services (ASMS), a consortium of Edward C. Levy Co. of Detroit, MI, and Queensland Cement Co., a wholly owned subsidiary of Holderbank Co. Approximately 1.3 million tons of blast furnace slag was processed into 700,000 tons of air-cooled slag and 600,000 tons of granulated slag. Approximately 50% to 60% of both types was used for road pavements, concrete aggregate, and cement manufacture, and the rest was stockpiled. Approximately 500,000 tons of basic oxygen furnace slag was produced, with 100,000 tons used for road pavements and the rest stockpiled.

Significant progress was made in the recognition of blast furnace slag as a heavy-duty pavement material with its use as a subbase layer for the third runway at Sydney's major airport. About 300,000 tons of a blast furnace slag mix was supplied to the project. Competition from other aggregates, including mined aggregate, was intense for this and all other civil projects in the Port Kembla area.

BHP Steel began construction of its No. 6 blast furnace at Port Kembla. The furnace had a nominal rating of 7,000 tons of iron per day and was scheduled to begin operations in late 1996. When fully operational, two smaller furnaces, Nos. 2 and 4, were to be closed down. The No. 6 blast furnace had about the same capacity as Nos. 2 and 4; therefore, overall production of iron and slag was to remain unchanged.

In Newcastle, there were three slag contractors, Boral Quarries, of Boral Ltd.; Steel Cement, Ltd. (owned mainly by a consortium of Australian and Japanese companies); and Steelstone Services of Australia. The first two contractors produced approximately 500,000 tons of blast furnace slag; 50% was air-cooled slag used in road pavements and construction and 50% was granulated slag used in cement manufacture and road construction. The latter contractor produced about 200,000 tons of steel slag, of which 100,000 tons was used for road construction and the balance was stockpiled.

All blast furnace slag produced in Newcastle was productively used in the marketplace, and more could have been sold if it had been available. Sales were assisted by the shortage of natural rock close to the main market area. Small shipments of granulated blast furnace slag were exported to Hawaii where its silicate content was used as a soil conditioner.

The State Roads and Traffic Authority of New South Wales was making extensive use of road pavement material in the Newcastle region comprising 70% basic oxygen furnace slag, 25% granulated blast furnace slag, and 5% fly ash. The use of the steel furnace slag mix as road pavement material was expected to be expanded. All of the components in the mix were byproducts from the BHP steel mill.

Electric arc furnace slag was also produced in Melbourne, Victoria, and Newcastle and Sydney in New South Wales.

Deep lift road stabilization was being increasingly used by the State Roads and Traffic Authority in several Australian states. Ground granulated blast furnace slag was frequently used either by itself or in combination with lime or fly ash.

Blast furnace slag cement marketed in Australia conformed to Australian Standard AS 1317. AS 1317 permitted slag to represent 20% to 65% of the total cementitious content.[3]

Following the release of a booklet entitled "A Guide to the Use of Slag in Roads", the Australasian Slag Association prepared a second booklet, "A Guide to the Use of Blast Furnace Slag in Cement and Concrete". It was to be released in 1995.

Austria.—Blast furnace slag and basic oxygen furnace steel slag consumption amounted respectively to 1.1 million and 0.395 million tons per year.

Belgium.—All production of blast furnace slag, about 2.4 million tons in 1994, was granulated and utilized by the cement industry in order to produce metallurgical cement. The most common cement sold on the Belgian market contained 40% crushed granulated blast furnace slag.

Basic oxygen furnace slag production remained similar compared with prior years, although some additional quantities of electric arc furnace slags were produced as a consequence of the startup of various electric arc furnace plants in Belgium and Luxembourg. The applications for steel slag remained principally for forest, farm and industrial roads, parking lots, stabilization of deposits, and hydraulic engineering. With the increasing availability of various secondary materials for civil construction, it was foreseen that there would be more competition for use of blast furnace slag.

France.—In 1994, approximately 2.37 million tons of granulated, 1 million tons of air-cooled, and 0.5 million tons of slag that was pelletized or processed in other ways was produced. Sollac had two granulating operations at Dunkerque and Fos, producing 0.960 and 0.460 million tons in 1994. Hayange at Rombas granulated 0.950 million tons of slag. Lafarge planned to build a 0.4 million ton granulator at Fos in 1996 or 1997, and Sollace was to build another one at Dunkerque.

Germany.—There were 7.77 million tons of blast furnace slag produced in Germany and 7.52 million tons sold, compared with 6.81 and 7.41 million tons, respectively, in 1993. Almost 93% of the slag produced came from nonphosphorus pig iron production, 2% from basic Bessemer pig iron production, and 2% from special pig iron production. There was an additional 3% from stocks of slag produced in prior years. About 48% of the slag was air-cooled slag used for road construction, 47% was granulated slag for cement, and nearly 4% was granulated slag for road construction. Foamed slag for road construction was not produced in 1994, and less than 1% was air-cooled slag for fertilizer.

There was 4.86 million tons of steel slag produced in Germany, and 4.64 million tons sold, compared respectively with 4.24 million produced and 3.73 million sold in 1993. Sixty percent was used as aggregate for roads, 19% was recycled back to the blast furnace, 11% was used for landfill, 6% was used as fertilizer, and 4% was for other uses.

Slag used in Germany must conform to special requirements for leachability, in addition to conforming to certain technological requirements. The leaching was done according to German Standard DIN 38 414. There were no common limits within Germany for the application of byproducts. Therefore, the state of Northrhine-Westfalia (Nordrhein-Westfalen) created special limits for each of 11 byproducts. According to the leachability of the slags, they could be used as aggregates in nearly all fields of applications as in road construction in asphalt or unbound layers.

India.—The Tata Group, one of the largest industrial forces in India, operated an integrated steel plant at Jamshedpur, Bihar in India. More than 0.72 million tons of slag per year was granulated. A 1.73-million-ton-per-year cement plant was built in order to utilize this granulated blast furnace slag. The unit of the plant which was to produce 1 million tons of clinker per year and 0.3 million tons per year of portland cement unit was installed at Sonadih, Madhya Pradesh, and a grinding plant able to produce 1.43 million tons per year of portland cement was installed at Jojobera, Bihar.[4]

Japan.— A total volume of 4 million tons of ground granulated blast furnace slag was produced with about 400,000 tons being exported to Southeast Asia.

Netherlands.—Blast furnace slag production amounted to about 1.2 million tons. Ninety-six percent of the iron slag was granulated and almost entirely sold to the cement industry. A small quantity was used in admixtures for road building. The remaining slag was air-cooled and used as a component for road building.

Steel slag production from basic oxygen furnace steelmaking amounted to about 530,000 tons. About 15% of this steel slag was returned to the furnace as process slag, 30% was used in marine engineering, and 15% was used in road construction as the main component in mixtures with granules. The remaining 40% was put in stock and could be used in large projects as a replacement for sand.

Much attention was given to upgrade steel slag by means of separation, quality control and aging so that it would be an acceptable replacement for natural aggregates used in road construction, concrete products, and cement production.

United Kingdom.—The amount of blast furnace slag produced in 1994 was approximately 3.46 million tons, about 5% more than that in 1993. The percentage of granulated slag and pelletized slag was about 31% of the total blast furnace slag. Slag was granulated and pelletized at Redcar, Scunthorpe, Llanwern and Port Talbot, with respectively, 0.3 million, 0.4 million, 0.25 million, and 0.2 million tons being produced.

Approximately 1.6 million tons of basic oxygen slag was produced, about 7% more than in 1993. British Steel Teeside marketed approximately 10,000 to 20,000 tons of basic oxygen slag as an agricultural liming fertilizer.

The principal means of regulating slag was the British Standard (BS). In addition, other Digests issued by the Building Research Establishment, although not carrying the force of a BS, were conformed to by slag processors. BS 6699 was used for blast furnace slag used in cement, ground granulated blast furnace slag (ggbfs). This ggbfs was for supply directly to the concrete manufacturer, ready-mixed, site-mixed, or precast. The BRE Digest No. 363 covered sulfate resistance of concrete and specified a 14% maximum Al_2O_3 content. BS 1047 covered air-cooled blast furnace slag for aggregates.

Current Research and Technology

A study was conducted at the Ashikaga Institute of Technology in Ashikaga, Japan.[5] Its purpose was to examine closely the basic properties of ordinary portland cement concrete, which contains finely granulated blast furnace slag and then to identify an appropriate method of applying the blast furnace slag to concrete. In the experiment, the ratio of cement replaced with ground granulated blast furnace slag was 30%, 50%, or 70%, the ratio of water to the cement plus ground granulated blast furnace slag was 35%, 45%, or 55%, the slump 18 plus or minus 2.5 centimeters (cm) and the air content approximately 5%. It was determined that when used as an additive for concrete, the fine granulated blast furnace slag could provide the specific concrete quality which met the application purpose.

Work was done at the Universitat GH Siegen in Germany to develop an injection mortar based on blast furnace slag, gypsum and Portland cement.[6] In the second part of the work, the aggregate was varied while retaining the same binder composition. The purpose was to reduce the water demand without impairing the other properties of the mortar. Various nodular materials and additives were used for this purpose. The fresh mortar was tested for water retention capacity, air void content and bulk density, and the hardened mortar for swelling and contraction, dynamic elastic modulus, compressive and flexural tensile strengths, water absorption, tendency to efflorescence, leaching behavior and porosity. From the results, it was seen that partial replacement of the standard sand by fly ash did not result in improvement in the water demand, but partial replacement of the standard sand by solid glass microspheres reduced the water demand without impairing the other properties tested.

Various results were obtained by using blast furnace slag for oil field use. Two refined and practical conversion methods of drilling mud to oilwell cement were proposed.[7] According to the Fluids Research Association, each method claimed universal applicability and performance superior to that of conventionally mixed and pumped portland cement. Blast furnace slag and portland cement were used for the drilling mud conversion.

An investigation of slurries using field and laboratory prepared drilling fluids solidified with blast furnace slag was undertaken at the Mobil E&P Technical Center.[8] In the investigation, data included base mud properties, final slurry composition, and slurry properties. Measurements were taken of the common properties of thickening times, compressive strength, free water, among others. It also included an evaluation of the bulk shrinkage of the set material, shear bond, as well as rheological compatibility studies of the finished slurries with the base muds. The additional tests were considered critical in the potential application of the process under field conditions. Operational considerations and the economics of required mud isolation and storage were reviewed. From the laboratory data evaluated, and environmental and economic evaluations, it was apparent that the use of blast furnace slag slurries for oil field applications was to be carefully evaluated on a case by case basis. The replacement of portland cement by the blast furnace slag slurry was thought to compromise some properties considered essential in a cementing operation.

Thorough testing, economic evaluations, and environmental evaluations of blast furnace slag slurries revealed that replacing portland cement with slag slurries may compromise essential properties in a cementing operation.[9] It was determined that the use of blast furnace slag slurries should be analyzed on a per case basis for oil well cementing operations. Test results indicated that blast furnace slag slurries could be designed to give good placement times and show compressive strength development over a wide temperature range. Stress cracking of blast furnace slag slurries was severe and occurred in atmospheric, pressurized, and constant temperature testing.

Blast furnace slag based cements were used by Shell Oil on over 160 oil well cementing operations as part of an effort to develop and expand the understanding of blast furnace slag cements.[10] Blast furnace slag cements decreased the remedial squeezing of casing shoes by 61% on exploratory wells drilled with subsea wellheads in the Gulf of Mexico.

Application of blast furnace slag in the cementing of oil and gas wells emphasizing the suitability of blast furnace slag for offshore operations in the North Sea was studied at the Rogaland Research Institute.[11] The study outlined the chemical reactions which occur during curing of blast furnace slag and discussed effects of different blast furnace slag sources and testing requirements. The application of blast furnace slag as a drilling fluid additive to improve cement bonding by solidification of the filter cake was discussed with respect to the effects of blast furnace slag on drilling fluid rheology and fluid loss. Blast furnace slag was found to be suitable for low volume operations such as plug cementing, however wider use of blast furnace slag was seen to be limited by logistics and occupational safety aspects for offshore North Sea applications.

The influence of the addition of 15% and 30% fly ash, 15% and 30% of a Greek natural pozzolan and 50% granulated blast furnace slag to ordinary Portland cement on the corrosion resistance of the reinforcing bars was studied in a program of long-term exposure to seawater.[12] The use of blended cements resulted in a decrease in the corrosion rate, especially after long exposure times. The most effective protection was provided by the 30% fly ash mix. This performance was related to the chloride content and the chloride binding capacity of the blended cements.

A study reported on by the British Cement Association in Berkshire, England, was concerned with measurements of corrosion in steel rods embedded at 2, 4, 8, and 12 millimeters (mm) from the exposed surface of concrete dried and carbonated uniaxially for 0.5, 1.5 and 4 years.[13] Corrosion was stimulated by exposing all specimens to a moist environment for a prescribed period prior to extraction and cleaning of the rods for gravimetric corrosion measurements. The work examined the effects of five water/cement ratios, four cements, three periods of moist curing, and five exposure conditions upon the carbonation-induced corrosion of the steel rods. Corrosion seemed to increase when there was 50% ground granulated blast furnace slag in the cement; in contrast, 30% pulverized fuel ash or 5% ground limestone had little effect. Investigationswere carried out at the King Fahd University of Petroleum and Minerals in Dhahran, Saudi Arabia, on blended cements incorporating blast furnace slag. One study was designed to evaluate the relative corrosion and sulfate resistance of concrete made with portland cements with and without 50%, 60%, 70%, and 80% cement replacement by blast furnace slag.[14] The results showed that blast furnace slag blended cement concretes had a significantly superior corrosion-resistance performance. The best corrosion protection was obtained with 50% blast furnace slag cement, which showed a 3 to 4 times better performance in terms of corrosion-initiation time compared with the parent plain cement concrete. Blast furnace slag blending was especially beneficial in improving the corrosion-resistance performance of Type V cements. Performance on exposure to sodium-sulfate solution, replacement level, only at 70% and above, showed sulfate resistance to be better than that of the Type V sulfate-resistant cement. Blast furnace slag blending imparted a high degree of sulfate resistance. However, with magnesium-gypsum type of attack, the 60% blast furnace slag cement deteriorated even more severely than the plain Type V and Type I cements.

Another investigation carried out at the King Fahd University had as its goal to determine the role of chloride ions in sulfate attack in plain and blended cements.[15] Paste and mortar specimens made with Type I and Type V cements as well as with Type I cement blended with fly ash, silica fume and blast furnace slag were exposed to four sulphate and/or chloride environments for a period of 2 years. The performance of these cements was evaluated through visual inspection and measurement of reduction in compressive strength. X-ray diffraction and scanning electron microscopic techniques were used to study the sulfate attack mechanisms in plain and blended cements in both the presence and the absence of chloride ions. Results indicated that sulfate deterioration in plain cements was mitigated by the presence of chloride ions, whereas in blended cements, particularly those made with silica fume and blast furnace slag, the beneficial effect of chloride was only marginal. This was attributed to the magnesium oriented sulfate attack that was more operative in blended cements.

Chloride-induced corrosion causes significant deterioration in transportation structures where uncoated reinforcing steel is used. Concretes with very low permeability were used to prevent the intrusion of chlorides into concrete to the level of the reinforcing steel. A study evaluated the strength and permeability of various combinations of silica fume and slag in concrete.[16] It was determined that when silica fume was added in small amounts of 3% to 5% to concretes with up to 47% slag at a water-cement ratio of 0.40 and 0.45, economical concretes with very low permeability and adequate strength could be produced.

Researchers at the University of Laval in Quebec City, measured pore solution chemistry, or high pressure extraction method, of cement pastes made with two condensed silica fumes, three pulverized fly ashes, and one ground granulated blast furnace slag, after a range of 7 to 545 days of curing at 38° C.[17] For all of the supplementary cementing materials (SCM's) in the study, a higher overall concrete alkali content, called for a higher cement replacement; an excessive alkali content could make the SCM totally ineffective, even with relatively high SCM contents.

Blended cement concretes incorporating blast furnace slag and condensed silica fume were tested for elastic modulus, creep and shrinkage strains, in order to compare their performance with that of plain Portland cement concretes.[18] Exposed and sealed specimens were investigated. The results showed that the exposure condition of the specimens during testing was critical. The addition of slag had the effect of causing a possible small increase in creep and shrinkage at early ages in exposed specimens, but this effect was usually reversed at later ages. Strains were markedly reduced in sealed slag specimens. The use of a blended cement resulted in less variability in cumulative strains.

The effect of cement, admixture, water-binder ratio and volume concentration of aggregate, on autogenous shrinkage of cement based materials was experimentally investigated.[19] A large amount of autogenous shrinkage was observed in cement paste and concrete with a very low water-binder ratio. Autogenous shrinkage was increased by using blast furnace slag with greater fineness. Other admixtures could decrease autogenous shrinkage.

Alkali-activated slag fly ash was developed to counteract the problem of severe attack on sewer concrete caused by biogenic sulfuric acid.[20] The hydraulic binder, Diabind, was composed of blast furnace slag, fly ash, sodium metasilicate, and a small amount of Portland cement clinker. The optimum composition of the binder was a compromise between acid resistance and strength. Diabind was successfully produced for use in concrete sewer pipes in industrial installations.

Research on artificial soft rock was carried out in Japan in order to investigate the durability of rock made from clay pulverized natural mud-rock, natural sand, water and new blended blast furnace slag cement mixtures.[21] In the experiment, the artificial soft rock specimens were exposed to various curing conditions in order to eliminate the temperature effect and to various water and weathering conditions in order to eliminate the resistance against the actions of various ground water and weathering for about 10 years. These studies proved that the artificial soft rock was highly resistant against the actions of various ground water and weathering. Their long-term durability was also verified by results of follow-up investigations, after exposing them in the field for 10 years.

Cements play a major role in the engineered structures for low and intermediate-level radioactive wastes.[22] Cement can effectively mobilize radionuclides as part of the overall multibarrier design of repositories. Immobilization timescales for radioactive wastes are long, of the order of 10^6 years for some radionuclides. Proof of the long-term performance of cements has placed new demands on investigations of cements used for this purpose. The chemistry of slag blends differs markedly from that of other blend types in its sulfide content. Most hydrated portland cements are mildly oxidizing. In slag cements, there is a critical blast furnace slag content beyond which a reducing environment is produced. High slag blends are particularly beneficial for treating wastes containing certain species.

At the GK Williams Cooperative Research Centre for Extractive Metallurgy in Victoria, Australia, research was conducted on blast furnace slags containing toxic elements.[23] Four slag types covering the range of Fe-Ca-Si-O compositions and two iron blast furnace slags were melted at 1,300º C and doped with 1% each arsenic, antimony, cadmium, zinc and chromium. The melts were either slow cooled or quenched, and the solidified slags were leached according to Toxic Characteristic Leachate Procedures. The morphology of the solidified slags was characterized using X-ray diffraction, optical and electron microprobe techniques. Theoretical considerations showed that the capacity of the molten slag to hold the above toxic elements depended upon slag basicity, which was confirmed in practice. The experiments showed that the leaching of the toxic elements was a function of surface area and the phases present, both of which were affected by the mode of cooling. Iron silicate slags produced in nonferrous smelting operations and blast furnace slag from ferrous smelting operations both have shown promise of being suitable media for immobilizing low levels of toxic elements and complying with regulatory requirements.

Blast furnace slags found many diverse uses in the ceramic industries. Iranian blast furnace slag was added for the first time to single fast fired wall tile compositions.[24] The chemical reactions occurring during firing and the formation of different phases were followed by differential thermal analysis, dilatometry, and X-ray diffractometry. The effects of composition on bend strength, water absorption, and firing shrinkage of differing compositions were investigated. An optimum slag content was found in the investigation to be 30%, which gave the best combination of less shrinkage, more water absorption, and lower bend strength.

Studies conducted at McMaster University in Hamilton, Ontario, dealt with the fact that when steel slag is used as an aggregate its properties depend upon its chemical and mineralogical composition.[25] The investigation used a detailed microscopic evaluation of specimens obtained from a steelmaking shop under well defined conditions. The variables of the study included chemical composition and cooling conditions.

Steel slag aggregate was used in premium surface course hot-mix asphalt for Ontario highways since the early 1970's. Asphalt pavement performance problems led to the Ministry of Transportation imposing a moratorium on the use of steel slag aggregate in late 1991. The problem was addressed from the steelmakers producing the slag through to hot-mix design and production.[26] Steel slag could make good aggregate for use in hot-mix asphalt if the volume expansion of the slag was controlled. Performance based testing of steel slag aggregate, particularly volume stability, was recommended as a measure of the aggregate quality and practices at the steelmaker and the slag processor were examined.

The International Iron and Steel Institute repeated a survey conducted in 1984, on the quantities and treatment of steel plant wastes and byproducts to determine changes in practice during the decade.[27] Results showed that there were reductions in some areas of byproducts generation, and in no area has the situation deteriorated since 1984. In particular, there was a reduction in blast furnace slag generation from an average of 311 kilograms per ton (kg/t) of hot metal. There was considerable improvement in recycling performance with respect to electric furnace dust. Its treatment is now well established and about 30% of all dust is processed to extract heavy metals.

At the National Center of Metallurgical Research in Madrid, Spain, blast furnace slag and electric arc furnace flue dust were vitrified through a gelification process. The use of slag or slag-derived gel produced a borosilicate glass with thermal properties similar to those of conventional sodium-calcium glass.[28] It was thought that the materials produced from blast furnace granulated slag could have an industrial application in the production of continuous filament fiber glass.

The latest developments in the disposal and application of iron and steel slag in Japan were described at the Shanghai Institute of Metallurgy in Shanghai, China.[29] Such developments included the air-granulated slag process, ultrafine blast furnace slag, color sand, recovery of the useful constituents in steel slag, water penetrating and antiwear material for pavement, spray abrasives for grinding ship surfaces, and water purification agents.

Outlook

Blast furnace slag consumption was expected to stay approximately the same in the next few years, with little increase in production of blast furnace slag and consistent usage. Granulated slag might increase its proportion of the total blast furnace market over the next few years as the cement industry seeks to utilize it to replace portland cement. The stockpiling of steel slag may continue as the production of the steel slag has outstripped its demand.

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TABLE 1
IRON AND STEEL SLAGS SOLD OR USED 1/ IN THE UNITED STATES 2/

(Thousand metric tons and thousand dollars)

Year	Blast furnace slag						Steel slag		Total slag	
	Air-cooled		Expanded 3/		Total iron slag					
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
1993	10,500	61,700	1,860	41,900	12,300	104,000	6,670	22,900	19,000	126,000
1994	10,700	62,400	1,600	51,100	12,300	114,000	7,800	26,900	20,100	140,000

1/ Value based on selling price at plant. Includes estimated value data for several operations.
2/ Previously published and 1994 data are rounded by the U.S. Bureau of Mines to three significant digits; may not add to totals shown.
3/ Includes granulated to avoid disclosing company proprietary data.

TABLE 2
BLAST FURNACE SLAGS SOLD OR USED IN THE UNITED STATES, BY REGION AND STATE 1/

(Thousand metric tons and thousand dollars)

	1993				1994			
	Air-cooled, screened and unscreened		Total, all types		Air-cooled, screened and unscreened		Total, all types	
	Quantity	Value 2/	Quantity	Value 2/	Quantity	Value 2/	Quantity	Value 2/
North Central:								
Illinois, Indiana, Michigan, Ohio	6,920	40,500	8,080	55,300	6,940	40,600	7,600	54,800
Middle Atlantic:								
Maryland, New York, West Virginia, Pennsylvania	2,030 r/	13,000 r/	2,990 r/	41,600 r/	2,040	13,400	3,000	50,700
Undistributed 3/	1,530 r/	8,170 r/	1,270 r/	6,670 r/	1,720	8,490	1,700	8,090
Grand total	10,500	61,700	12,300	104,000	10,700	62,400	12,300	114,000

r/ Revised.
1/ Previously published and 1994 data are rounded by the U.S. Bureau of Mines to three significant digits; may not add to totals shown.
2/ Value based on selling price at plant.
3/ Includes Alabama, California, Kentucky and Utah.

TABLE 3
PROCESSORS OF IRON AND STEEL SLAG IN THE UNITED STATES IN 1994

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 Service	Blytheville, AR				X	--
Do.	Kankakee, IL				X	--
Do.	Charlotte, NC				X	--
Do.	Holsopple, PA				X	--
Do.	Washington, PA				X	--
Do.	Cayce, SC				X	--
Do.	Darlington, SC				X	--
Do.	Seguin, TX				X	--
Do.	Plymouth, UT				X	--
Blue Circle Atlantic Inc.	Sparrows Point, MD	X				Granulated.
Buffalo Crushed Stone	Buffalo, NY	X				Air-cooled.
C. J. Langenfelder	Baltimore, MD		X			--
Do.	Braddock, PA		X			--
CSR America	Middletown, OH	X				Air-cooled.
Dunbar Slag Co. Inc.	Wheatland, PA	X		X		Do.
Heckett Co.	Fontana, CA	X				Do.
Do.	Wilton, IA				X	--
Do.	Chicago, IL	X				Air-cooled.
Do.	Sterling, IL				X	--
Do.	East Chicago, IN		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 City, MO				X	--
Do.	Canton, OH		X			--
Do. (Warren Plant)	Warren, OH		X			--
Do.	do.				X	--
Do.	Youngstown, OH				X	--
Do.	Butler, PA				X	--
Do.	Provo, UT	X		X		Air-cooled.
Do.	Seattle, WA				X	--
International Mill Service	Fort Smith, AR				X	--
Do.	Pueblo, CO		X			--
Do.	Claymont, DE				X	--
Do.	Tampa, FL				X	--
Do.	Cartersville, GA				X	--
Do.	Alton, IL				X	--
Do.	Chicago, IL	X			X	Air-cooled.
Do.	Granite City, IL		X			--
Do.	Huntington, IN				X	--
Do.	Laplace, LA				X	--
Do.	Jackson, MI				X	--
Do.	Monroe, MI				X	--
Do.	St. Paul, MN				X	--
Do.	Perth Amboy, NJ				X	--
Do.	Riverton, NJ				X	--
Do.	Marion, OH				X	--
Do.	Middletown, OH		X		X	--
Do.	Mingo Junction, OH		X		X	--
Do.	Sand Springs, OK				X	--
Do.	McMinnville, OR				X	--
Do.	Portland, OR				X	--
Do.	Beaver Falls, PA				X	--
Do.	Burgettstown, PA				X	--
Do.	Coatesville, PA				X	--
Do.	Midland, PA				X	--
Do.	Pricedale, PA		X		X	--

TABLE 3 - Continued
PROCESSORS OF IRON AND STEEL SLAG IN THE UNITED STATES IN 1994

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	Reading, PA				X	--
Do.	Georgetown, SC				X	--
Do.	Jackson, TN				X	--
Do.	Beaumont, TX				X	--
Do.	Jewett, TX				X	--
Do.	Longview, TX				X	--
Do.	Midlothian, TX				X	--
Do.	Saukville, WI				X	--
Do.	Weirton, WV		X			--
Koch Minerals	Gary, IN	X				Air-cooled, expanded and granulated.
Do.	Weirton, WV	X				Granulated.
Edward C. Levy Co.	Detroit, MI	X	X		X	Air-cooled and expanded.
The Levy Co. Inc.	Burns Harbor, IN	X	X			Air-cooled.
Do.	East Chicago, IN	X				Do.
Maryland Slag Co.	Sparrows Point, MD	X				Do.
Standard LaFarge Co.	Granite City, IL	X				Do.
Do.	Cleveland, OH	X				Air-cooled and expanded.
Do.	Cuyahoga, OH			X		--
Do.	Lordstown, OH	X		X		Granulated.
Do.	McDonald, OH			X		--
Do.	Mingo Junction, OH	X				Air-cooled.
Do.	Warren, OH	X				Do.
Do.	Youngstown, OH			X		--
Do.	Penn Hills, PA			X		--
Do.	West Aliquippa, PA	X				--
Do. (Brown Reserve)	West Mifflin, PA	X				Air-cooled.
Do. (Duquesne)	do.	X	X	X		Do.
Do.	Weirton, WV	X				Do.
Stein, Inc.	Cleveland, OH		X			--
Do.	Lorain, OH		X			--
United Slag Co.	Rancho Cucamonga, CA				X	--
Vulcan	Alabama City, AL	X				Air-cooled.
Do.	Fairfield, AL	X	X			Do.
Waylite Corp.	Bethlehem, PA	X	X	X		Air-cooled and expanded.

TABLE 4
AIR - COOLED BLAST FURNACE SLAG SOLD
OR USED IN THE UNITED STATES, BY USE 1/ 2/

(Thousand metric tons and thousand dollars)

Use	1993 Quantity	1993 Value	1994 Quantity	1994 Value
Asphaltic concrete aggregate	2,050	13,100	1,940	12,200
Concrete aggregate	1,000	7,410	1,180	8,540
Concrete products	442	2,250	498	3,120
Fill	1,460	6,410	870	3,030
Glass manufacture	W	W	W	W
Mineral wool	507	3,620	621	4,430
Railroad ballast	157	678	188	867
Road bases	4,380	23,400	4,850	26,500
Roofing, built-up and shingles	43	538	71	946
Sewage treatment	W	W	W	W
Soil conditioning	W	W	W	W
Other 3/	439	4,290	475	2,800
Total	10,500	61,700	10,700	62,400

W Withheld to avoid disclosing company proprietary data; included with "Other."
1/ Previously published and 1994 data are rounded by the U.S. Bureau of Mines to three significant digits; may not add to totals shown.
2/ Value based on selling price at plant.
3/ Includes ice control, miscellaneous and uses indicated by symbol "W."

TABLE 5
STEEL SLAG SOLD OR USED IN THE UNITED STATES, BY USE 1/ 2/

(Thousand metric tons and thousand dollars)

Use	1993 Quantity	1993 Value	1994 Quantity	1994 Value
Asphaltic concrete aggregate	1,090	4,920	1,140	5,000
Fill	905	2,370	1,320	3,750
Railroad ballast	116	323	160	467
Road bases	2,660	8,120	3,170	11,300
Other 3/	1,900	7,130	2,000	6,400
Total	6,670	22,900	7,800	26,900

1/ Previously published and 1994 data are rounded by the U.S. Bureau of Mines to three significant digits; may not add to totals shown.
2/ Excludes tonnage returned to furnace for charge material. Value based on selling price at plant.
3/ Includes ice control, soil conditioning, and miscellaneous uses.

TABLE 6
SHIPMENTS OF IRON AND STEEL SLAG IN THE UNITED STATES IN 1994, BY METHOD OF TRANSPORTATION 1/

Method of transportation	Quantity (thousand metric tons)
Truck	17,000
Waterway	837
Rail	886
Not transported (used at plant site)	1,360
Total	20,100

1/ Data rounded by the U.S. Bureau of Mines to three significant digits; may not add to total shown.

TABLE 7
AVERAGE VALUE PER TON AT THE PLANT FOR IRON AND STEEL SLAG SOLD OR USED IN THE UNITED STATES, BY TYPE

(Dollars per metric ton)

Year	Iron blast furnace slag		Steel slag	Total slag
	Air-cooled	Total iron slag		
1993	5.89	8.40	3.43	6.65
1994	5.84	9.23	3.45	6.99

TABLE 8
AVERAGE SELLING PRICE AND RANGE OF SELLING PRICES AT THE PLANT FOR IRON AND STEEL SLAG IN THE UNITED STATES IN 1994, BY USE

(Dollars per metric tons)

Use	Iron blast furnace slag			
	Air-cooled		Steel slag	
	Average	Range	Average	Range
Asphaltic concrete aggregate	4.54	3.73- 10.84	2.72	1.92- 8.61
Cement manufacture	W	W	W	W
Concrete products	4.54	W	--	--
Fill	2.72	1.61- 6.36	1.81	1.17- 4.45
Glass manufacture	W	W	W	W
Mineral wool	5.44	4.54- 8.18	--	--
Railroad ballast	3.63	2.51- 7.71	1.81	2.20- 5.94
Road bases	3.63	2.07- 7.26	2.72	.84- 10.36
Roofing, built-up and shingles	10.89	5.53- 63.29	--	--
Sewage treatment	W	W	W	W
Soil conditioning	W	W	W	W
Other	4.54	1.91- 8.58	1.81	.45- 4.37

W Withheld to avoid disclosing company proprietary data.