PROPERTIES AND USES OF IRON AND STEEL SLAGS

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Slags from the iron and steel industries are sometimes erroneously classified, and often looked upon, as industrial waste materials. In actual fact, these by-products are valuable and extremely versatile construction materials. The history of slag use in road building dates back to the time of the Roman Empire, some 2000 years ago, when broken slag from the crude iron-making forges of that era were used in base construction. Applications were quite sporadic until the last century, when large quantities began to be used for a number of purposes. In relatively recent years, the need for maximum utilization and recycling of by-products and recovered waste materials for economic and environmental reasons has led to rapid development of slag utilization. In some areas, nearly all of the iron and steel slags are now being used, and use is rapidly growing in many others.

This discussion will briefly cover the composition, properties, and uses of iron blast-furnace slags and of steelmaking slags. The major basis will naturally be the experience developed in the U.S., with mention of the uses in other countries. Although other slags are sometimes used, only the major slags produced by the iron and steel industries will be considered.

IRON BLAST-FURNACE SLAG

Blast-furnace slag is defined by the American Society for Testing and Materials as "the non-metallic product consisting essentially of silicates and alumino-silicates of calcium and other bases that is "developed in a molten condition simultaneously with iron in a blast furnace." The blast furnace is the primary means for reducing iron oxides to molten, metallic iron. It is continuously charged with iron oxide sources (ores, pellets, sinter, etc.), flux stone (limestone and dolomite), and fuel (coke). Molten iron collects in the bottom of the furnace and the liquid slag floats on it. Both are periodically tapped from the furnace.

The slag consists primarily of the impurities from the iron ore (chiefly silica and alumina) combined with calcium and magnesium oxides from the flux stone. Sulfur and ash that may come from the coke will also be contained in the slag, which comes from the furnace as a liquid at temperatures about 1500°C. It is a man-made molten rock, similar in many respects to volcanic lavas.

CHEMICAL AND MINERALOGIC COMPOSITION

Chemical analyses of blast-furnace slags usually show that the four major oxides (lime, magnesia, silica and alumina) make up about 95% of the total. Minor elements include sulfur, iron, manganese, alkalis, and trace amounts of several others.

Most of the blast-furnace slags produced in the U.S. have compositions within the ranges shown here:

Table 1 Major Chemical Constituents in Blast Furnace Slag

Constituent	Weight Percent
Lime (CaO)	32 to 45
Magnesia (MgO)	5 to 15
Silica ($Si0_2$)	32 to 42
Alumina(Al_20_3)	7 to 16
Sulfur (S)	1 to 2
Iron Oxide (Fe_20_3)	0.1 to 1.5
Manganese Oxide (MnO)	0.2 to 1.0

The majority of the slags produced in other nations also seem to fall in, or near, these composition ranges.

The chemical composition of the slag is dependent upon the composition of the available iron ores, flux stones, and fuels, and on the proportions required for efficient furnace operations. The blast furnace must be charged with uniform raw materials if the iron produced is to be consistent in quality. This procedure also insures uniformity in the composition of the slag, and as a result the composition of slag from a given source varies within relatively narrow limits. Greater variations, as shown in the overall ranges above, may be found between sources where different raw materials are being used.

Slag that is cooled rapidly after emerging from the furnace tends to form a glassy, non-crystalline material. Slower cooling leads to crystallization of a number of minerals; the most common ones are shown in Table 2.

Melilite, the name applied to any of the continuous series of solid solutions formed by akermanite and gehlenite, is the most common mineral in slag. The other minerals are present or absent depending upon relative proportions of the major oxides in the slag; most slags contain not more than four of the minerals. The mineral dicalcium silicate; may form in slags high in lime, and cause disintegration upon cooling by a volume increase when changing from one crystalline form to another. The sulfur in slow-cooled slag usually appears as sulfides of calcium, iron and manganese.

Table 2 Minerals of Air-cooled Blast Furnace Slag

Mineral	Formula
Akermanite	$2CaO\text{-}MgO\text{-}2SiO_2$
Gehlenite	$2CaO\text{-}Al_20_3\text{-}SiO_2$
Wollastonite	$CaO\text{-}SiO_2$
Dicalcium silicate	$2CaO\text{-}SiO_2$
Merwinite	$3CaO\text{-}Mgo\text{-}2SiO_2$
Anorthite	$CaO\text{-}Al_2O_3\text{-}2SiO_2$
Monticellite	$CaO\text{-}MgO\text{-}SiO_2$

The chemical composition of blast-furnace slag is a significant factor in the potential performance of granulated material in cementitious uses. For chemical uses, such as a raw material for manufacture of glass or mineral wool insulation and for agricultural applications, the chemical composition is quite important. While of lesser importance in aggregate uses, the chemical composition does directly affect the slag viscosity and the rate of crystallization during cooling, and thereby influences the porosIty and the character and size of crystals in the solidified slag. The slag processor cannot control the chemical composition, which is dependent upon the available raw materials and requirements for an efficient iron-making operation; he can only modify the slag properties to a limited extent by changing cooling conditions. It is fortunate, therefore, that the range of slag compositions associated with good iron production is all useful construction materials, although varying in physical properties.

Nonetheless, there are factors of performance as related to composition that should be mentioned. As noted previously, slow-cooled, high-lime slags may form dicalcium silicate that undergoes a volume increase on cooling to ambient temperatures. This results in the "dusting" or "falling" of the slag, literally reducing it to a powder. Compositional changes can be readily made to avoid such problems, which are basically of concern only to the producers whose potential product is destroyed. Experience indicates that disintegration will occur, in susceptible slags, prior to construction use and is not a problem for the ultimate user. Rapid cooling also obviates any problems in slags destined for cementitious or chemical uses by preventing crystallization of the dicalcium silicate.

Iron unsoundness is a rarely encountered problem that has been reported in Europe. Slags high in iron oxides may, with appropriate levels of other constituents, form compounds that will readily react with water, with resultant disintegration of the slag. In slags with usual ranges of iron contents, it is not a problem; in others it is easily detected by immersing the slag in water.

Sulfur has long been looked upon as an undesirable component, primarily because of suspicions that one reaction or another "is possible" or "might cause a problem" of some kind. In actual practice no correlation of sulfur content with performance seems to exist. Some leaching of sulfur compounds from uncoated slag does occur. The leachates are not poisonous in nature, occur only under poor drainage conditions, and are temporary or transient in existence. The worst effects, unpleasant odors from stagnant water in slag fills or bases, are in the "nuisance" category and are avoidable by proper design considerations

PHYSICAL PROPERTIES

Blast-furnace slag is tapped from the furnace as a liquid, which contains gases held in solution. The conditions of cooling control both the growth of mineral crystals and the quantity and size of gas bubbles that can escape before being trapped by solidification of the slag mass. Thus, within the limits Imposed by the particular chemical composition, the cooling conditions determine the crystalline structure and the density and porosity of the slag. Dependent upon the cooling methods employed, any of three distinctly different types of product may be made from the molten blast-furnace slag.

Air-cooled blast-furnace slag is permitted to solidify under the prevailing atmospheric conditions, either in a pit adjacent to the furnace, or in one some distance away to which it is transported in large ladles. After solidification, the cooling may be accelerated by water sprays that produce cracking, and facilitate digging of the slag. The product is predominantly crystalline in nature, with a cellular or vesicular structure resulting from bubbles of gases that were dissolved in the molten slag. After cooling, the slag is dug, crushed, and screened to the desired sizes. Metallic iron in the slag is removed by powerful magnets in the crushing and screening plant.

The air-cooled slag crushes to angular, roughly cubical particles with pitted surfaces. Excellent bond is provided with either hydraulic cements or bituminous binder materials. High internal friction values and particle interlock provide excellent stability when used without cements. Bulk specific gravity and unit weight are dependent upon grading and particle size; the larger particles contain more internal cells or vesicules and have a lower bulk density. The coarse sizes may have bulk densities as much as 20% lower than natural aggregates with the same gradation, while the fine material (passing a 4.75mm sieve) is nearly equal to natural sand in density. The aggregate is highly resistant to weathering effects, and does not readily polish to produce slippery surfaces. The air-cooled slag coarse aggregates are usually classified with crushed stones and gravels as "normal weight" aggregates. They are used for all types of construction applications, just as the natural aggregates are; however, the weight saving in the case of slag becomes a significant factor in some applications.

Granulated blast-furnace slag is produced by quickly quenching (chilling) molten slag to produce a glassy, granular product. The most common process is quenching with water, but air or a combination of air and water may be used. Very little mineral crystallization takes place in the very rapid cooling process. The granulated slag may vary from a friable, popcorn-like structure to small, sand-size grains resembling a dense glass, depending upon the chemical composition, temperature at the time of quenching, and the cooling rate.

The slag glass contains the same major oxides as does Portland cement, but with considerably different proportions of lime and silica. Like Portland cement, it has excellent hydraulic properties and, with a suitable activator (such as calcium hydroxide) will set in a similar manner. Granulated slags may be crushed, graded or ground for specific applications.

Expanded blast-furnace slag (also called "foamed slag") results from treatment of molten slag with controlled quantities of water, less than that required for granulation. A number of pit and machine processes have been developed to combine the molten slag with water, or with water and air or steam. The resulting product is more cellular or vesicular in nature than the air-cooled slags, and is much lighter in unit weight. Variations in the amount of water and the process used control the cooling rate, and can result in product variations from highly crystalline materials resembling very vesicular air-cooled slags to glassy materials closely akin to granulated slag. A pelletizing process recently developed in Canada uses limited amounts of water followed by chilling of slag droplets thrown through the air by a rapidly revolving finned drum. This produces spherical pellets of highly glassy slag. Expanded slag particles, depending upon the processing procedure, may be either angular and roughly cubical in shape or may be spherical and smooth surfaced. The cellular structure results in densities in the lightweight aggregate categories. Many of the expanded slags possess cementitious properties attributable to high glass content.

USE OF BLAST-FURNACE SLAG

Use of slags developed in iron making dates back many centuries; in the U.S. blast-furnace slag had been used in road building as long ago as 1830, as railroad ballast since 1875, use as concrete aggregate began in the 1880's and in bituminous surfaces in the early 1900's. Major development of slag uses was in the construction aggregate applications, with much smaller amounts going into more specialized applications such as cement manufacture and agricultural applications. For the past 25 years essentially all the blast-furnace slag produced in the nation has been used. This level of commercial application has been reached on a competitive basis with other materials; the slag has been used either because it can provide equal performance at a lower cost, or better performance for similar cost.

In a typical year, 1978, about 28.4 million tons (25.4 x 106Mg) of blast-furnace slag was used in the U.S. This amount of slag was divided among the different types as follows:

1978	1992[1]
Air Cooled- 88%	Air Cooled - 90%
Granulated - 5%	Granulated & Expanded - 7%
Expanded - 10%	

Air-cooled slag *uses* were many and varied, including all types of construction aggregate applications in addition to manufacture of mineral wool, cement and glass and as a soil conditioner. The principal uses as percentages of the total air-cooled slag were:

	1978	1992[2]
Road Bases	35%	46%
Asphalt concrete aggregate	16%	16%
Concrete aggregate	12%	10%
Structural fill	11%	10%
Railroad ballast	10%	1%
Mineral wool	4%	6%

Other aggregate applications included roofing, sewage plant filter media and drainage works.

The major application is primarily in untreated in base courses, with smaller amounts used in bases stabilized with cement, asphalt, or lime-fly ash mixes. In all types of base construction, the slag is used in precisely the same manner as would any crushed, natural material. The slag has a number of desirable characteristics for this type of construction, including:

(a) particle shape and texture that provides exceptionally high stability
(b) non-plastic fines
(c) volume stability under all weathering conditions
(d) lower weight per unit volume

The same benefits are applicable to the use in structural fills, where the lower weight is particularly important in reducing dead load on weak or unstable soils. Similar considerations are, of course, important in railroad ballast which also ranks among the five largest uses. The applications in bases, fill and ballast combined make up some 56% of the total slag tonnages marketed; all are dependent upon the strength, stability, and durability properties of the aggregate.

The second largest use of the air-cooled slag, as aggregate in asphalt concrete, is one in which it is often the preferred material. In addition to the stability and durability characteristics mentioned above, the slag does not polish under traffic as do many natural aggregates. The slags are among the best materials to provide safe, skid-resistant surface courses and are specified for this purpose in some areas. All blast-furnace slags are alkaline in reaction, coat readily with asphalt, and are not subject to stripping problems.

In concrete aggregate use, the air-cooled slag offers properties of excellent bond with the cement, freedom from deleterious particles and alkali reactions, volume stability and durability, good concrete strengths and fire resistance superior to that obtained with other normal weight aggregates. The slag aggregate concretes are usually made with slag coarse aggregate and natural sand fine aggregate for workability. Structural dead loads are decreased because the unit weights of the slag concretes are normally about 160 kg/m^3 less than those obtained with other types of aggregates.

Granulated blast-furnace slag use was quite small as noted above. Of the total, 84 % was used in road base and fill construction and 8 % as concrete fine aggregate. Other reportable uses included cement, drainage work and soil conditioning. The amount used in cement was very small, but interest in cementitious applications is growing rapidly in the U.S. Large increases in this use are expected in the next several years, with a large part of the development along the lines of .Slagment in South Africa - the slag being used as a separately ground cementitious material added at the mixer.

Expanded slag use was largely for lightweight concrete aggregate, much of it in concrete block and other precast units. Nearly 90% of the expanded slag was used in concrete, where it provides better thermal insulation and fire resistance properties than obtainable with comparable concretes made with other aggregates. Other uses included cement manufacture, drainage facilities and use as a lightweight fill material specified under particularly adverse soil conditions.

World-wide use of blast-furnace slag has reached a high percentage of the total production. A recent survey of utilization indicated a number of countries in which 90% or more of the blast-furnace slag produced was being utilized. Development of use in Great Britain has been roughly parallel to that in the U.S., and for the same general types of application. Britain does use, at the present time, a lower percentage of the slag as concrete aggregate and more in cement. Use in bases and in bituminous construction is also somewhat higher than in the U. S.

In many other nations, the percentage of blast-furnace slag that is granulated is much higher than ours; in some cases exceeding 50% of the total. Overall, the blast-furnace slags appear to be used primarily in road construction (bases fills, bituminous paving), with nearly 50% of the total going into those applications. Nearly 30% is used in cement, either to make Portland cement clinker or in blended cement applications. The next largest single use world-wide appears to be as concrete aggregate, with air-cooled and expanded materials together representing about 10% of this use. There are large variations in relative use ratios in different countries due to differing needs and economic situations.

BLAST-FURNACE SLAG SPECIFICATIONS

About a century ago, when use of blast-furnace slags in cement began to develop, fears arose that the sulfur in slag could oxidize and cause expansion of the concrete, that it could generate acid and corrode the reinforcing steel, etc. These fears were transferred to aggregate usage with the idea that adjacent metals or concrete could be attacked. Later, more ghosts were raised - the voids in slag could cause failures in freezing and thawing, the presence of magnesia might result in the formation of expansive periclase and disrupt structures; "falling" slags might fall or disintegrate after incorporation in a structure rather than at the time of cooling. None of these horrible things have happened in a century of use of more than one and one-half billion tons of blast-furnace slag in the U.S. alone. It is doubtful that any such disasters took place anywhere else. Nevertheless, the specifications for slags in many countries impose unnecessary and unreasonable restrictions designed to prevent something that has never occurred in practice. Such restrictions have a habit of spreading, and finding application in one area solely because it is customary that such a limit should be imposed and it really doesn't do any harm - all of the available slags pass the test.

In the aggregates area, unnecessary requirements can, and do in some countries, prevent the use of perfectly usable materials, sometimes because of efforts to make slag fit the requirements believed reasonable for natural aggregates. Blast-furnace slag is a different material, different in particle shape, mineralogy, porosity characteristics, density, etc. It cannot be expected to fit precisely the mold made for another material.

The national specifications for slag in the U.S. for aggregate applications utilize the same required gradings as for other aggregates. Requirements for durability, freedom from deleterious materials, etc. are generally the same. The abrasion test requirements (used as a measure of strength) are generally waived for slags because no correlation of performance with such tests has ever been established. Instead, the coarse aggregates are usually required to meet a minimum unit weight - a value that was found to correlate with strengths of concrete made with constant cement content and workability (slump). Weight requirements are not equal to weights of natural aggregates, but rather are values that will produce performance at least equal to that of good quality natural aggregates. (Expanded slag for lightweight aggregate is subject to a maximum unit weight requirement, as are all lightweight aggregates.)

There are no general chemical requirements; there have never been any indications that any would be useful or desirable. We oppose the use, on specific projects, of special requirements based solely on the fact that they have been used somewhere or on a laboratory test under different conditions half a world away. Useful specifications can only be based on the local materials available, the construction requirements and experience in that area.

Procedures for proportioning of mixtures containing slag are the same as those for other aggregate materials with, of course, appropriate consideration of the different bulk density, absorption, specific gravity, etc. compared to natural aggregates. With proper proportioning of mixtures, construction procedures are no different than for other materials.

STEELMAKING SLAGS

Steelmaking slags are the by-products of processing molten iron into a specific type or grade of steel. Open-hearth, basic-oxygen and electric furnaces are the principal types used in steel production. The slags are often referred to by the type of furnace - open-hearth slags, BOF slags, electric-furnace slags - or simply as "steel slags" in the U.S. In other countries they may have other names - converter slags, LD slags, etc.

Steel making is a "batch" process; the furnace is charged with the necessary hot and/or cold metal, the composition is adjusted and alloying materials added to produce the desired composition of steel. Both the molten steel and slag are then emptied from the furnace and the process repeated. Practically all steel slags are air-cooled. The steelmaking slags are produced in smaller quantities than are the blast-furnace slags and are less widely used. They will be discussed only briefly.

Composition and Properties

Steelmaking slags are composed principally of calcium silicates, calcium alumino-ferrites, and fused oxides of calcium, iron, magnesium, and manganese. The compositions vary with type of furnace, composition of furnace charges, grades of steel produced, and with individual furnace operating practices. Materials added to the melt just before the end of a heat may not be completely incorporated in the slag. Therefore, some free oxides, including CaO, may be found in some slags.

Compared to blast-furnace slags, the steelmaking slags usually contain much higher amounts of iron and manganese, are lower in silica and may be higher in lime producing a much higher lime-silica ratio, and sulfur contents are usually quite low. Physically, the steelmaking slags are much heavier, harder, denser and less vesicular in nature, and have unusually high resistance to polishing and wear.

Use of Steelmaking Slags

Use of steelmaking slags developed later than that of blast-furnace slags and has not progressed as far. Early processing was solely for metallics recovery, with the slag wasted. Some of the early attempts to use these as aggregates were unsuccessful due to volume changes from hydration of CaO (and MgO from burned dolomite from furnace linings in some open-hearth slags). These difficulties, usually associated with use of fresh (and often unprocessed) materials in rigidly confined locations, where even small amounts of expansion would be detrimental, inhibited rapid development of further uses.

Present day steelmaking slags are being successfully used in two major types of applications: (a) as a source of iron and flux materials in blast furnaces, and (b) as a high quality mineral aggregate for specific uses. No volume change problems have been encountered in uses such as unpaved shoulders or bases, for erosion control, as railroad ballast, or in asphalt pavement surfaces where the slags have demonstrated outstanding skid-resistant properties.

Uses in bases and structural fills, where very high stabilities are obtained, may require proper selection, processing and aging (weathering) before use. Use in rigidly confined applications - such as concrete aggregate or as fill under building floors and inside foundation walls, is not recommended.

It is estimated that one-half to two-thirds of the steel slags produced world-wide are used, either by recycling or in road building applications, railroad ballast, as fertilizers, etc. 1978 use in the U.S. for construction purposes totaled nearly 8.5 million tons, with major uses as follows:

	1978	1992[3]
Road bases	57%	35%
Fill	21%	16%
Asphalt aggregate	7%	13%
Railroad ballast	6%	3%

Miscellaneous uses included ice control, soil conditioning, raw material for cement manufacture, etc.

Specifications

The only nationally recognized specification for steelmaking slags in the U.S. is for use as railroad ballast.[4] Other than imposing a minimum unit weight; the requirements are identical to those for other aggregate. In all other cases, the specifications for steel slags are local in nature, being fitted to the materials available in the particular area. Both specification requirements and permissible uses vary from state to state. In some cases, specific aging or weathering requirements are stipulated to hydrate free lime prior to use. Several efforts are underway to develop test procedures by which potential expansion can be determined.[5] In other areas, the only uses permitted are those for which no expansion problems are known to exist. Specifications and tests to evaluate these characteristics are also under development in other countries.

Notes:

1) 1992 *Slag - Iron and Steel Annual Report,* U.S. Bureau of Mines, p. 9.
2) 1992 *Slag - Iron and Steel Annual Report,* U.S. Bureau of Mines, p. 13.
3) 1992 *Slag - Iron and Steel Annual Report,* U.S. Bureau of Mines, p. 14.
4) In 1991 ASTM published a Standard Specification for Steel Slag Aggregates for Bituminous Paving Mixtures - Designation D5106.
5) In 1988 ASTM published a Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions - Designation D4792.

GENERAL REFERENCES

1. Josephson, G. W., Sillers, F. and Runner, D. G., "Iron Blast-Furnace Slag: Production, Processing, Properties, and Uses, U.S. Bureau of Mines Bulletin 479, Washington, D.C., 1949.
2. Lee, A. R., "Blast Furnace and Steel Slag", Edward Arnold (Publishers) LTD, London, 1974.
3. "Processed Blast-Furnace Slag: The All-Purpose Construction Aggregate", NSA 179-1 1978.
4. Lewis, D. W., "Resource Conservation by Use of Iron and Steel Slags", Extending Aggregate Resources, ASTM Special Technical Publication, ASTM, 1982.