NATIONAL SLAG ASSOCIATION

Proudly Serving The Industry For Over 100 Years

Blast Furnace Slag

The Choice Construction Material

Presented by the NSA

PROVIDING SOLUTIONS

INCREASING PRODUCTIVITY

REDUCING COSTS

LIMITING LIABILITY

SUSTAINING THE ENVIRONMENT

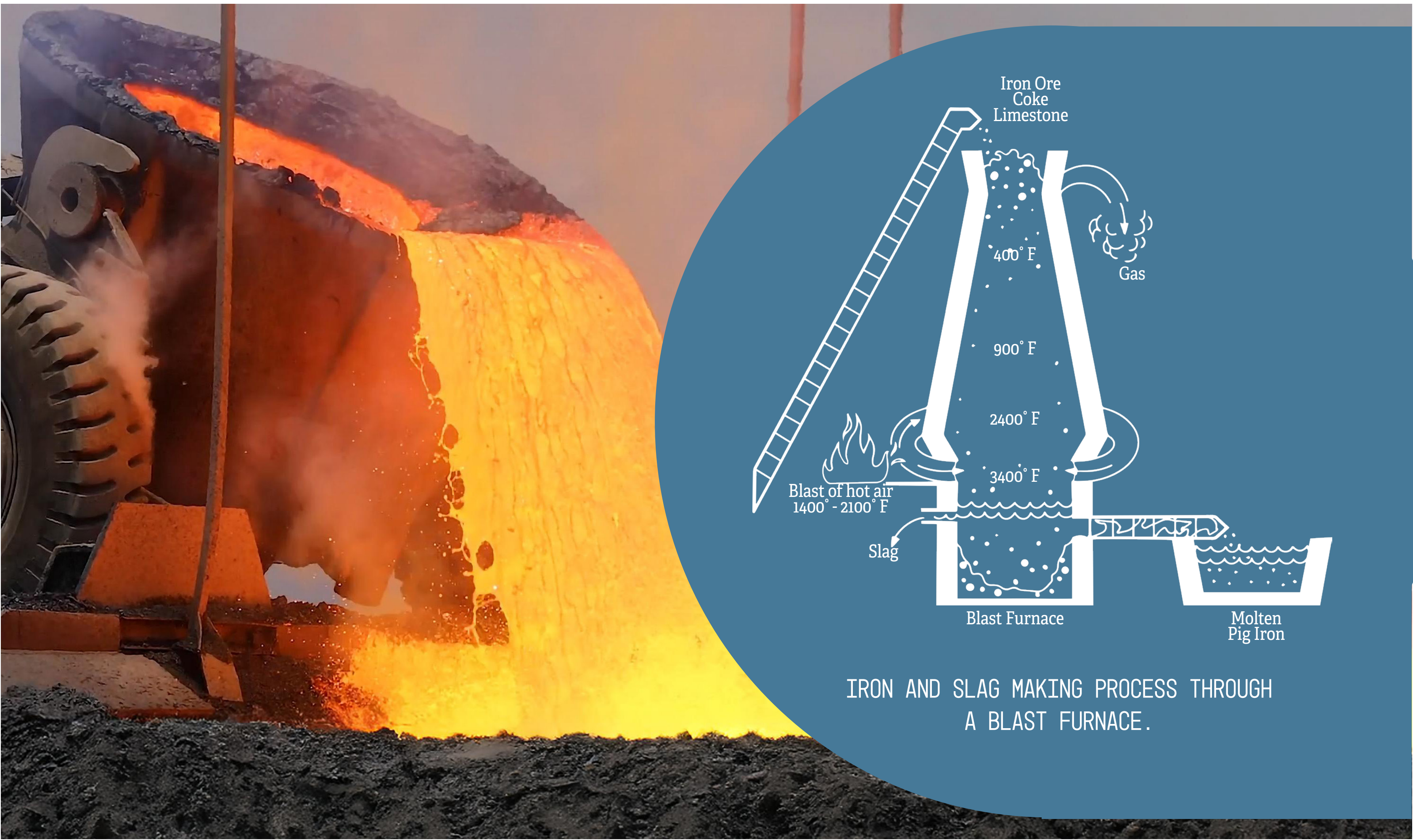
THE ALL PURPOSE CONSTRUCTION AGGREGATE

At the turn of the twentieth century, producers of pig iron were exploring possible applications for slag, which was an iron byproduct from their furnaces. In 1908, Carnegie Steel launched a study to investigate various potential uses of slag. As early as 1911, a Carnegie report titled "Furnace Slag in Concrete" established slag as a suitable product for use as an aggregate in concrete.

In 1917, it was evident that slag had become a valuable product, and producing companies would benefit from a more united promotional effort. It was also apparent that slag operators were having difficulty obtaining railroad cars due to the war effort, necessitating a cooperative effort to acquire them. In 1918, ten men met in Columbus, Ohio, and voted to organize the National Slag Association. A 1919 survey by the U.S. Bureau of Public Roads concluded that there were 32 plants operated by 14 companies producing slag.

Slag has evolved from it's origins as a road-building aggregate in Ancient Rome to its present-day status as a value-added construction material with diverse applications. Through modern, state-of-the-art processing methods, slag has applications in nearly every facet of the construction industry, including ground granulated blast furnace slag (GGBFS), blended cements, lightweight hydraulic fill, masonry, structural concrete, asphaltic concrete, granular base aggregate, railroad ballast, mineral wool, roofing, soil conditioning, glass, and many others.

The united effort of today's National Slag Association (NSA) members, worldwide, is the driving force that makes slag "the construction material of choice". This effort represents a continued emphasis on providing innovative, value-added quality products to the construction industry well into the new millennium.



IRON AND SLAG MAKING PROCESS THROUGH A BLAST FURNACE.

DEFINITION AND DESCRIPTION OF SLAG

The American Society of Testing and Materials (ASTM C125-21 Definition of Terms Relating to Concrete and Concrete Materials) defines blast furnace slag 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".

In the production of iron, the blast furnace is charged with iron ore, flux stone (limestone and/or dolomite), and coke for fuel. The furnace yields two products: molten iron and slag. The slag consists primarily of silica and alumina from the original iron ore, combined as minerals which are comprised of mainly calcium and magnesium from the flux stone. Slag emerges from the furnace in a molten state with temperatures exceeding 1480˚C (2700˚F). There are four distinct methods of processing the molten slag: air cooled, expanded, pelletized, and granulated; each of these methods produces unique slag material.

DEFINITION & DESCRIPTION OF STEELS

The American Society for Testing Materials (ASTM) defines Steel Slag as a non-metallic product, consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium and magnesium, that is developed simultaneously with steel in basic oxygen, electric arc, or open hearth furnaces.

MINERAL CONSTITUENTS

The principle mineral constituents of blast furnace slag are melilite, merwinite, pseduowallastonite, and monticellite; which are primarily composed of silica, alumina, calcium, and magnesia, making up 95% of slag's total composition. The mineral constituents are engineered by changing the cooling rate process. Analysis of most blast furnace slags falls within the ranges shown below. In the case of granulated and pelletized slag, these elements primarily exist as amorphous glass. The chemical composition of slag from a given source varies within relatively narrow limits since raw materials charged into the furnace are carefully selected and blended.

PHYSICAL PROPERTIES

The physical characteristics (weight, particle size, structural properties, etc.) vary according to the method used in processing the molten slag. Accordingly, end use of the processed material varies, which helps to explain the unique diversity of slag products.

Table 1 Slag, Ferrous Metal, Blast Furnace (Air Cooled)

Major Primary Mineral Constituents	Molecular and Structural Formula
Melilite (solid solution between akermanite and gehlenite), calcium-aluminum-magnesium-silicate	$Ca_2MgSi_2O_7$ — $Ca_2Al_2SiO_7$
Merwinite, calcium-magnesium-silicate	$Ca_3MgSi_2O_8$
Pseudowollastonite, calcium-silicate	$CaSiO_3$
Monticellite	$CaMgSiO_4$
Amorphous	. . .

Adapted from ASTM D8021-2

TYPES OF BLAST FURNACE SLAG PROCESSING

AIR-COOLED/ATMOSPHERIC COOLING

EXTREMELY VERSATILE & DURABLE BUILDING MATERIAL

DESCRIPTION

Air-Cooled Blast Furnace Slag (ACBFS) as defined in ASTM C 125-21a is: "The material resulting from solidification of molten blast-furnace slag under atmospheric conditions; . Subsequent cooling may be accelerated by application of water to the solidified surface".

TEXTURE AND SHAPE

The solidified slag characteristically has a porous structure with many non-connected cells. ACBFS crushes to angular, roughly cubical pieces with minimal flat or elongated fragments. The rough porous texture of slag gives it a greater surface area than smoother aggregates of equal volume and provides an excellent bond with portland cement and high stability in asphalt mixtures. For embankment applications, the rough surfaces improve the angle of internal friction or interlocking of the pieces.

SPECIFIC GRAVITY

Due to the porous nature of ACBFS, it is important that bulk specific gravity be used rather than apparent specific gravity for purposes of computing yield or estimating quantities. The bulk specific gravity (dry basis) of ACBFS coarse aggregate generally falls in the range of 2.0 to 2.5. Since large pores cannot exist in small particles, the smaller size products have higher specific gravities. Slag sand (#4 to 0 size) approaches natural sand in bulk specific gravity.

UNIT WEIGHT

The unit weight varies with: (a) size and grading of the slag, (b) method of measuring and (c) bulk specific gravity of the slag. Typical unit weight (compacted) of crushed and screened air-cooled slag, graded as ordinarily used in concrete, is usually in the range of 1121 kg to 1281 kg per m^3 (70 to 85 lb per ft^3). Slag has an economic advantage in construction because it has a lower unit weight than most natural aggregates. Allowance for this differential should always be considered for design and specifications to assure equal volume irrespective of the type of aggregate used.

GRADING

ACBFS is crushed and screened to conform to the grading requirements of the various state highway departments, municipalities and other specifying bodies. Gradations specified in national standards, such as ASTM D 448. Standard sizes of coarse aggregate for highway construction, are usually preferred and often the most readily available.

ABSORPTION

Water absorption of ACBFS is usually in the range of 1 to 5% by weight, as it has a greater surface area and lower specific gravity than most natural aggregates. The degree of saturation (portion of the total void space filled by water) is low. Due to its irregular surface, care must be taken when determining the surface dry condition when calculating absorption. The pores are similar to the air bubbles in air-entrained cement pastes and the resulting durability is outstanding.

RESISTANCE TO POLISHING

Notwithstanding its toughness, the degradation of slag, as tested in the Los Angeles (LA) abrasion machine, is generally higher than for round or smooth-surfaced natural aggregates. This is due mainly to the rough edges on the surface breaking off under impact of the steel balls constituting the test charge.

It has been proven that there is no correlation between the LA abrasion loss for slag in laboratory tests and degradation in field applications. For this reason ASTM exempts crushed slag from the degradation requirements in various specifications (see ASTM D 692, D1139, etc.); additionally D.O.T.'s in states where slag is available do not require LA abrasion testing for slag. LA Abrasion limits for slag, if included in specifications, should be somewhat higher than that for natural aggregates to a maximum of approximately 50% loss.

This higher loss, however, does not mean that slag is softer than natural aggregates. The hardness of slag as measured by the Mohs scale is between 5 & 6. This compares favorably with the hardness reported for such materials as durable igneous rocks. Investigations have shown that slag fines produced during the LA abrasion are crystalline and non-plastic.

THE CORE OF THE PROTECTIVE BREAKWATER AT THE HAMMOND MARINA (HAMMOND, IN.) CONSISTS OF 65,000 TONS OF ACBFS. AFTER EXTENSIVE TESTING, INDIANA'S DEPARTMENT OF ENVIRONMENTAL MANAGEMENT APPROVED ACBFS AS AN ACCEPTABLE PRODUCT FOR USE IN LAKE MICHIGAN.

AN OUTSTANDING CHARACTERISTIC OF ACBFS IS ITS TOUGHNESS AND RESISTANCE TO POLISHING UNDER TRAFFIC.

NON-CORROSIVE

The small amounts of sulfur in slag are present in combined alkaline minerals, similar to those found in portland cement. These are harmless to concrete and do not cause corrosion of reinforcing steel. The corrosive properties of coal ash or cinders should not be mistakenly applied to blast furnace slag. Examination of reinforcing bars taken from slag concrete structures after 30 years of service has shown no evidence of corrosion.

DURABILITY

Slag is highly resistant to environmental degradation. It will withstand an unusually large number of cycles of the sulfate soundness test (ASTM C 88). Freezing and thawing or wetting and drying tests, also have little or no effect. High temperatures have very little effect on slag as it is formed in the blast furnace at about 1480˚C or 2700˚F. ACBFS shows a slow but very uniform coefficient of expansion of approximately 0.000006 per ˚F, up to its melting point (1150-1426˚C/2100-2600˚F). This figure is normally accepted as the coefficient of expansion for cement mortar and steel, hence, slag, when combined with these ingredients to form reinforced concrete, affords a high degree of compatibility.

APPLICATIONS

- Concrete
- Asphaltic Pavement
- Lightweight Embankment
- Waterway Applications
- Masonry Units
- Mineral Wool
- Soil Conditioning
- Metallurgical Flux
- Glass Making

AREAS OF ADDED VALUE

- Excellent paste - aggregate bond in concrete
- Greater yield for all construction applications
- Improved skid resistance and stability in asphaltic pavements
- High angle of internal friction resulting in improved aggregate interlock
- Lower unit weight/improved engineering properties for lightweight embankment
- Improved fire resistance for masonry and concrete applications
- Lower freight and labor costs due to lower unit weight
- Replenishes soil with minerals and balances pH
- Economical alternative to Wollastonite as key ingredient in metallurgical mold powders and flux products
- Physical and chemical suitability for mineral wool production

TYPES OF BLAST FURNACE SLAG PROCESSING

CONTROLLED WATER-COOLING /EXPANDED

ENGINEERED, LIGHTWEIGHT POROUS MATERIAL OBTAINED BY CONTROLLED PROCESSING

THE PROCESS

Controlled quantities of water are used to accelerate the solidification process of molten blast furnace slag, resulting in a low density material. The solidified expanded slag is crushed and screened for use as a lightweight structural aggregate

TEXTURE AND SHAPE

Expanded blast furnace slag is angular and cubical in shape, with negligible flat or elongated particles. Due to the action of the water and resulting steam on the solidification process, the open cellular structure of the particles is even more pronounced than particles of air cooled blast furnace slag.

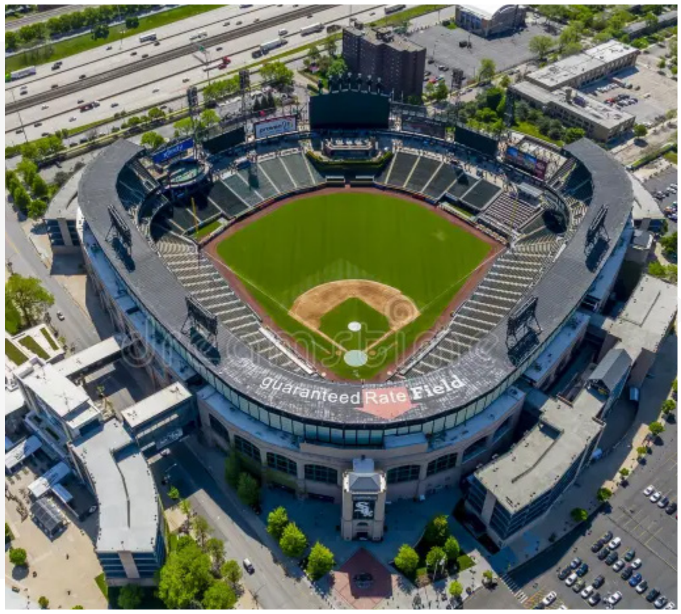
GRADING

Expanded blast furnace slag is crushed and screened to desired product sizing. Typically this is a blend of coarse and fine aggregate particles. The actual grading of products should be reviewed with the local supplier.

FIRE RESISTANCE RATINGS OF WALLS AND PARTITIONS (AMERICAN INSURANCE ASSOCIATION)

Types of Coarse Aggregate	Minimum Equivalent Thickness for Ratings of:			
	4 hrs.	3 hrs.	2 hrs.	1 hr.
Expanded Blast Furnace Slag or Pumice	4.7	4.0	3.2	2.1
Expanded Clay or Shale	5.7	4.8	3.8	2.6
Limestone, Cinders or Air Cooled Blast Furnace Slag	5.9	5.0	4.0	2.7
Calcareous Gravel	6.2	5.3	4.2	2.8
Siliceous Gravel	6.7	5.7	4.5	3.0

COMISKEY PARK (CHICAGO, IL) BUILT IN EARLY 90'S CONTAINS OVER 900,000 LIGHTWEIGHT CONCRETE BLOCK, USED EXPANDED **BLAST FURNACE SLAG AGGREGATE** IN ORDER TO ACHIEVE THE DESIRED WEIGHT, AS WELL AS FIRE RESISTANCE REQUIREMENTS.



APPLICATIONS

- Medium to Lightweight Concrete Masonry Units
- Lightweight Embankment -Medium to Lightweight
- Structural Concrete

AREAS OF ADDED VALUE

- Improvements in fire resistance ratings have also been documented for masonry and structural concrete units made from expanded blast furnace slag aggregate, (see the table above) representing the findings of the American Insurance Association
- Expanded blast furnace slag aggregate is a specialty product made for the masonry block industry
- Masonry units containing expanded blast furnace slag aggregate possess many desirable properties such as reduced weight, improved sound absorption and excellent thermal properties
- Substantial improvements in labor efficiencies can also be realized as masons can handle and place more lower weight units per day.

TYPES OF BLAST FURNACE SLAG PROCESSING

WATER QUENCHING /GRANULATED

GLASSY, GRANULAR MATERIAL FORMED WHEN SLAG IS RAPIDLY CHILLED, AS BY IMMERSION IN WATER

THE PROCESS

The most common process for granulating blast furnace slag involves the use of high water volume, high pressure water jets in direct contact with the molten blast furnace slag at a ratio of approximately 10:1 by mass. The molten blast furnace slag is quenched almost immediately, forming a material generally smaller than a #4 sieve.

When granulated blast furnace slag is formed, it must be de-watered, dried and ground, using processes similar to those used with portland cement clinker to make portland cement.

Typically, granulated slag is finely ground (measured by the Blaine test), exceeding the fineness of portland cement to obtain increased hydraulic activity at early ages. As with portland cement and pozzolans, the rate of reaction increases with the particle fineness.

GROUND GRANULATED BLAST FURNACE (GGBFS) SLAG

When GGBFS slag is mixed with water, initial hydration is much slower as compared with portland cement. Therefore, portland cement or alkali salts are used to increase the reaction rate. In the hydration process, GGBFS slag produces calcium silicate hydrate cement paste. This valuable contribution from GGBFS slag improves the paste-to-aggregate bond in concrete. GGBFS slag mixtures with portland cement typically result in greater strength and reduced permeability.

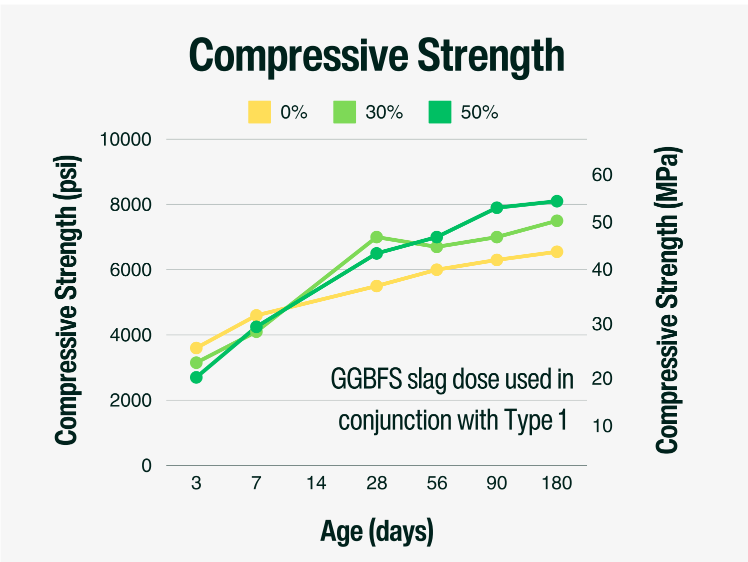
ASTM C989 provides three strength grades of GGBFS slag, depending on their respective mortar strengths when blended with an equal amount of portland cement. As summarized below, the classifications are grade 80, 100 and 120, based on the slag activity index. (See chart on the next page.)

TABLE 1 PHYSICAL REQUIREMENTS

Fineness:		
Amount retained when wet screened on 45µm (No. 325) sieve, max %		20
Specific surface by air permeability, Test Method C204 shall be determined and reported although no limits are required.		...
Air Content of Slag Mortar, max %		12
	Average of Last Five Consecutive Samples	**Any Individual Sample**
Slag Activity Index[1]		
28-Day Index, min %		
Grade 80	75	70
Grade 100	95	90
Grade 120	115	110

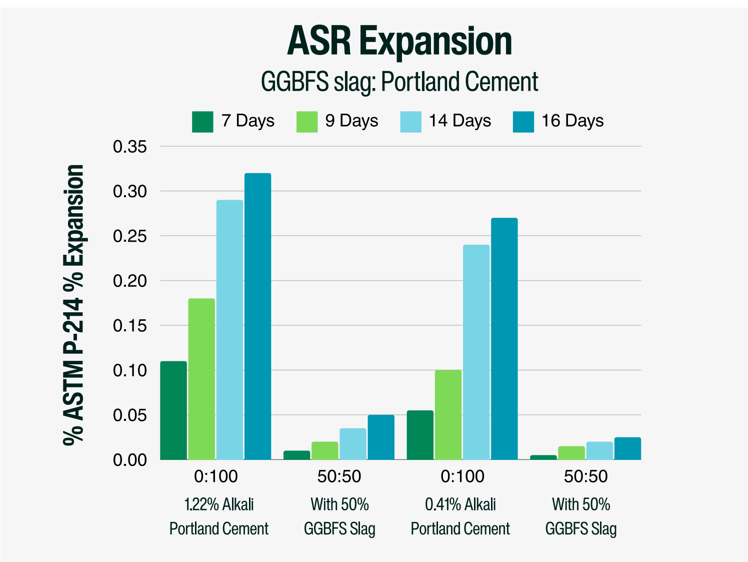
[1] 7-Day Slag Activity Index shall be determined on Grades 100 and 120, and reported for informational purposes.

STRENGTH DEVELOPMENT OF GGBFS SLAG (GRADE 100)



ASR EXPANSION

REDUCED ALKALI-SILICA REACTION



Color

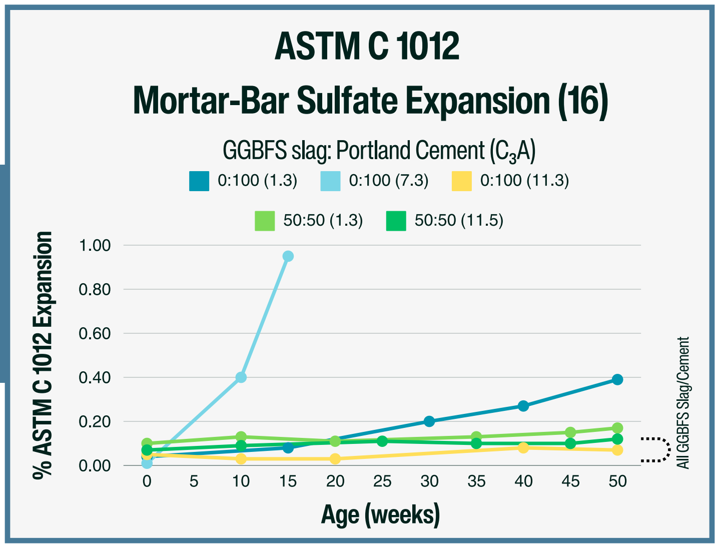
GGBFS slag is considerably lighter in color than most portland cements and will produce a lighter concrete end product. Occasionally, concrete containing GGBFS slag may exhibit a blue-green coloration. While this coloration effect seldom occurs, it is attributed to a complex reaction of the sulfide sulfur in the GGBFS slag with other compounds in the cement and will diminish with age.

SEACLIFF BRIDGE, STANWELL PARK ILLAWARRA NEW SOUTH WALES

THE SEA CLIFF BRIDGE TOGETHER WITH THE ADJOINING LAWRENCE HARGRAVE DRIVE BRIDGE, ARE TWO ROAD BRIDGES THAT CARRY THE SCENIC LAWRENCE HARGRAVE DRIVE ACROSS THE ROCKFACE ON THE ILLAWARRA ESCARPMENT, LOCATED IN THE NORTHERN ILLAWARRA REGION OF NEW SOUTH WALES, AUSTRALIA. OPEN 2005.

ASTM C 1012 MORTAR BAR EXPANSION

IMPROVED SULFATE RESISTANCE OVER TYPE V CEMENT



INSTALLATION OF HANBAR UNIT INTO SEAWALL @ PORT KEMBLA HARBOR, NEW SOUTH WALES.

PART OF A TRAIL USING ALKALI ACTIVATED FLY ASH AND SLAG CONCRETE OR GPC (GEOPOLYMER CONCRETE) NO CEMENT. 75% CO2-EEQ REDUCTION ON CONVENTIONAL CONCRETE. IMPROVED DURABILITY BASED ON IN FIELD MONITORING. INSTALLED IN 2019.

APPLICATIONS

- Raw material for the manufacture of cement
- Lightweight Fill
- Raw material for the manufacture of glass

FACTORS AFFECTING CEMENTITIOUS PROPERTIES

- Chemical composition of slag
- Alkali concentration of the reacting system
- Glass content of the GGBFS slag
- Fineness of the GGBFS slag

AREAS OF ADDED VALUE

SPECIALTY CONCRETE APPLICATIONS

- Reduced chloride permeability
  Improved resistance to sulfate attack
- Reduced heat of hydration in mass concrete
- Improved compressive and flexural strength
- Reduced alkali-silica reaction

ENVIRONMENTAL COMMITMENT

In the early 1900s, limited markets for steel slag led to millions of tons being stockpiled. Through the marketing and research efforts of the National Slag Associations' (NSA) member companies, steel slag is now recognized as a "premier construction aggregate" for many construction applications, utilizing over eight million tons annually in North America.

In 1995, the Steel Slag Coalition (SSC) was formed to provide industry with a comprehensive environmental assessment of blast furnace slag. This coalition, comprised of iron and steel manufacturers and slag processors, hired an independent nationally renowned chemical laboratory and risk assessment team to conduct a human and ecological health risk assessment of blast furnace slag. The risk assessment has since been updated several times and as recently as 2023. The risk assessment scientists analyzed samples from each participating company in accordance with EPA's risk assessment guidelines. The results of these studies reinforce that blast furnace slag conforms to EPA's stringent requirements and does not pose a threat to human or plant life. Consequently, it should continue to be recommended for a wide variety of construction applications. (Further information can be obtained through the NSA Office).

Leachate from steel-making slag can increase pH levels in ambient water due to its generally alkaline nature. The potential ecological risks related to elevated pH in slag leachate were considered by Proctor et al. (2002), who concluded that most aquatic environments (e.g., rivers and lakes) would not be threatened by slag application along their banks, because any slag leachate would be sufficiently diluted by the relatively large amounts of ambient water. To assess the impact of alkalinity from environmental applications of steel-making slag, it is recommended that users consider the scale of the potentially affected area, the potential for dilution, and the period of time during which the alkaline leachate is expected to continue (as the slag ages and the calcium hydroxide is armored). Laboratory studies of these environmental processes can provide additional information to assist in the evaluation of environmental applications. Accordingly, the potential for alkaline conditions should be considered for site-specific application scenarios where leachate from slag could reach ecological receptors. The alkalinity of slag leachate, however, is not expected to be a concern unless dilution with ambient water is less than approximately 100-fold, consistent with the conclusions of Proctor et al. (2002).

The National Slag Association and its member companies recognize their responsibility in protecting the environment and conserving the earth's natural resources. For this reason, they will continue to remain committed to researching and recommending responsible end uses for this environmentally safe, manufactured aggregate.

National Slag Association

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