The Construction Material of Choice

NATIONAL SLAG ASSOCIATION
At the turn of the Twentieth Century, producers of pig iron began to look into possible applications for slag which was being produced simultaneously with the iron coming from their furnaces. In 1908 Carnegie Steel launched a study to look for a variety of possible uses of slag. As early as 1911, a Carnegie report, “Furnace Slag in Concrete” established a position for 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, and a cooperative effort was needed to acquire them. In 1918 ten men met in Columbus, Ohio and voted to organize the National Slag Association. The U.S. Bureau of Public Roads concluded in a 1919 survey that there were 32 plants being operated by 14 companies producing slag.

Slag has transcended its beginnings as a road building aggregate in Ancient Rome, to its present day status as a value added construction material with diverse applications. By way of modern, state of the art processing methods, slag has present day 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, natural soil, roofing, soil conditioning, glass, and many others.

The united effort of today’s National Slag Association 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.

**Definition and Description of Slag**

The All-Purpose Construction Aggregate

The American Society of Testing and Materials (ASTM C125) 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. Two products are obtained from the furnace: molten iron and slag. The slag consists primarily of the silica and alumina from the original iron ore, combined with calcium and magnesium oxides from the flux stone. It comes from the furnace 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 a unique slag material.

**Chemical Properties**

The principle constituents of blast furnace slag are silica, alumina, calcium, and magnesium (reported as oxides), which comprise 95% of slag’s total makeup. Minor elements include manganese, iron and sulfur compounds as well as trace quantities of several others. Analysis of most blast furnace slags fall within the ranges that are shown below. It should be noted, however, that the major oxides shown do not occur in free form in the slag. In air-cooled BF slag, they are combined to form various silicate and alumino-silicate minerals such as mullite, merwinite, wollastonite, etc., as found in natural geological forms. In the case of granulated and pelletized slag, these elements exist primarily as 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.

**Typical Chemical Constituents**

<table>
<thead>
<tr>
<th>Element</th>
<th>Percent</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica (SiO₂)</td>
<td>32-42</td>
<td></td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td>7-16</td>
<td></td>
</tr>
<tr>
<td>Calcium (CaO)</td>
<td>32-45</td>
<td></td>
</tr>
<tr>
<td>Magnesium (MgO)</td>
<td>5-15</td>
<td></td>
</tr>
<tr>
<td>Iron Oxide (Fe₂O₃)</td>
<td>1-1.5</td>
<td></td>
</tr>
<tr>
<td>Sulfur (S)</td>
<td>*</td>
<td>1-2</td>
</tr>
</tbody>
</table>

*Sulfur occurs primarily in the form of calcium sulfide*
Types of Blast Furnace Slag Processing

**Air-Cooled**

**ATMOSPHERIC COOLING**

Extremely versatile and durable building material

**Texture and Shape**

The solidified slag characteristically has a vesicular structure with many non-connected cells. ACBF slag crushes to angular, roughly cubical pieces with a minimum of flat or elongated fragments. The rough vesicular 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 bituminous mixtures. For embankment applications, the rough surface improves the angle of internal friction or interlocking of the pieces.

**Specific Gravity**

The bulk specific gravity (dry basis) of ACBF slag, coarse aggregate generally falls in the range of 2.0 to 2.5. Since large vesicles cannot exist in small particles, the smaller size has higher specific gravities. Slag sand (0% to 15%) approaches natural sand in bulk specific gravity. Due to the cellular nature of slag, it is important that bulk specific gravity be used rather than apparent specific gravity for purposes of computing yield or estimating quantities.

**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 112 to 128 lb per cu ft or 70 to 95 lb per ft³. 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 in order to assure equal volume irrespective of the type of aggregate used.

**Grading**

ACBF slag 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 course aggregate for highway construction, are usually preferred and offer the most readily available.

**Resistance to Polishing**

An outstanding characteristic of ACBF slag is its toughness and resistance to polishing under traffic. Notwithstanding its toughness, the degradations of slag, as tested in the Los Angeles Abrasion machine, are generally higher 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 has deleted this test for slag in its specifications (see ASTM D-692, D1139, etc.) and D.O.T.'s in states where slag is available do not require this test 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 30% 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 and 6. This compares favorably with the hardness reported for such materials as durable igneous rocks. Tests show the fines resulting from the LA Abrasion test on slag to be non-plastic.

**Non-Corrosive**

The small amounts of sulfur in slag are present in combined alkaline compounds similar to that 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. The pit of solutions in contact with slag is always basic which tends to inhibit corrosion.

**Durability**

Slag is highly resistant to the action of weathering. It will withstand an unusually large number of cycles of the sulfate soundness test (ASTM C 136). 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. ACBF slag shows a slow but very uniform coefficient of expansion of approximately 0.000006 per degree F, up to its melting point (1150 to 1426C/2100 to 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 reinfored concrete, affords a high degree of compatibility.

**Applications**

- **Concrete**: Excellent paste-aggregate bond in concrete.
- **Asphaltic Pavement**: Greater yield for all construction applications.
- **Lightweight Embankment**: Improved skid resistance and stability in asphaltic pavements.
- **Waterway Applications**: High angle of internal friction resulting in improved aggregate interlock.
- **Masonry Units**: Lower unit weight.
- **Unreinforced Materials**: Improved engineering properties for lightweight embankment.
- **Mineral Wool**: Excellent fire resistance for masonry and concrete applications.
- **Soil Conditioning**: Improved fire resistance for masonry and concrete applications.
- **Flux Products**: Replenished soil with mineral and pH balance.
- **Metalurgical Products**: Economic alternative to Wolfsbrite as key ingredient in metallic mold powders and flux products.
- **Metallurial Flux Products**: Physical and chemical suitability for mineral wool production.
Types of Blast Furnace Slag Processing

Expanded Blast Furnace Slag

**CONTROLLED WATER-COOLING**

Lightweight vesicular material obtained by controlled processing

**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.

**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 solidification process of molten blast furnace slag is facilitated by the addition of water at this stage. The treatment of the molten blast furnace slag feed plate where it is quenched with water. The slag stream flows from the feed plate onto a vibrating state as they are launched through the air away from the pelletizer.

**Texture and Shape**

Pelletized slag is available in a number of sizes or gradations. The most common sizes processed are: Structural Coarse (1/2″ – 3/8″), Structural Fine (3/16″ – 1/8″), Structural Blend (3/16″ – 3/8″), and Blended (1/4″ – 1/8″). Densities range from 952 kg/m³ (59 lbs/ft³) to 1105 kg/m³ (69 lbs/ft³), depending on gradation.

**Applications**

- **MEDIUM TO LIGHTWEIGHT CONCRETE MASONRY UNITS**
- **MEDIUM TO LIGHTWEIGHT STRUCTURAL CONCRETE**

**Areas of Added Value**

- **Resistance to sulfate attack**
- **Facilitates “Value Added” Products**

**Fire Resistance Ratings** (American Insurance Association) Walls and Partitions

<table>
<thead>
<tr>
<th>Fire Resistance</th>
<th>Type of Course Aggregate</th>
<th>Minimum Exposed Thickness</th>
<th>For Ratings of</th>
<th>4 hrs</th>
<th>3 hrs</th>
<th>2 hrs</th>
<th>1 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expanded Blast Furnace Slag or Pumice</td>
<td>6.7</td>
<td>5.0</td>
<td>3.5</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded Clay or Shale</td>
<td>5.7</td>
<td>4.8</td>
<td>3.8</td>
<td>3.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone, Cinders or Air Cooled Blast Furnace Slag</td>
<td>5.9</td>
<td>5.0</td>
<td>4.0</td>
<td>2.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcium Slag</td>
<td>6.2</td>
<td>5.3</td>
<td>4.2</td>
<td>2.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siliceous Gavel</td>
<td>6.7</td>
<td>5.7</td>
<td>4.5</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ACCELERATED COOLING**

A Unique Process that Facilitates the Manufacture of “Value Added” Products

**The Process**

In the pelletizing process, a molten blast furnace slag stream is directed onto an inclined vibrating feed plate where it is quenched with water. The addition of water at this stage causes the slag to foam. While in this expanded pyroplastic state the slag stream flows from the feed plate onto a revolving finned drum. As the drum rotates, the fins repeatedly strike the slag stream with sufficient force to propel the slag into the air, dispensing it and forming spherical droplets. These droplets, or slag pellets, freeze rapidly to a solid state as they are launched through the air away from the pelletizer.

**Texture and Shape**

The treatment of the molten blast furnace slag with water and the resultant foaming action, lead to a unique internal cellular structure within each slag pellet. This cellular structure (many voids only detectable with the aid of an electron microscope) is contained within a smooth spherical skin. The combination of these characteristics leads to the formation of a low density aggregate, with diverse applications as a construction material.

**Gradations and Densities**

Pelletized slag is available in a number of sizes or gradations. The most common sizes processed are: Structural Coarse (1/2″ – 3/8″), Structural Fine (3/16″ – 1/8″), Structural Blend (3/16″ – 3/8″), and Blended (1/4″ – 1/8″). Densities range from 952 kg/m³ (59 lbs/ft³) to 1105 kg/m³ (69 lbs/ft³), depending on gradation.

**Applications**

- **RAW MATERIAL FOR THE MANUFACTURE OF SLAG CEMENT.**
- **MEDIUM TO LIGHTWEIGHT CONCRETE MASONRY UNITS.**
- **AGGREGATE FOR USE IN STRUCTURAL CONCRETE.**
- **LIGHTWEIGHT FILL.**
- **MASS CONCRETE PLACEMENT APPLICATIONS.**

**Areas of Added Value**

- **Facilitates “Value Added” products.**
- **Raw Material**
- **Improved workability**
- **Controls heat of hydration**
- **Resistance to sulfate attack**
- **Pelletized Aggregate**
- **Fire Resistance**
- **Sound absorption**
- **Thermal properties**
- **Reduction in “Dead Loads”**

**Sky Dome, Toronto, Canada**

**Sound Cell System™**

(of offered by Best Block & Richvale York Block)
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 to 1 by mass. The molten blast furnace slag is quenched almost immediately, forming a material generally smaller than a #4 sieve.

Ground Granulated Blast Furnace (GGBF) Slag
When GGBF 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, GGBF slag produces calcium silicate hydrate cement paste. This valuable contribution from GGBF slag improves the paste-to-aggregate bond in concrete. GGBF slag mixtures with portland cement typically result in greater strength and reduced permeability.

ASTM C989 provides three strength grades of GGBF 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 below.)

Color
GGBF slag is considerably lighter in color than most portland cements and will produce a lighter concrete end product. Occasionally, concrete containing GGBF 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 GGBF slag with other compounds in the cement and will diminish with age.

<table>
<thead>
<tr>
<th>ASTM C989 Slag Activity Index Standards</th>
<th>Slag-activity index</th>
<th>Minimum percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age and Grade</td>
<td>Average of last five consecutive samples</td>
<td>Any individual sample</td>
</tr>
<tr>
<td>7-day index</td>
<td>Grade 80: 75</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Grade 100: 95</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Grade 120: 120</td>
<td>120</td>
</tr>
<tr>
<td>28-day index</td>
<td>Grade 80: 75</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Grade 100: 95</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Grade 120: 120</td>
<td>110</td>
</tr>
</tbody>
</table>

Types of Blast Furnace Slag Processing

Granulated
WATER QUENCHING
Glassy, granular material formed when slag is rapidly chilled, as by immersion in water.

Factors Affecting Cementitious Properties
- Chemical composition of GGBF slag
- Alkali concentration of the reacting system
- Glass content of the GGBF slag
- Fineness of the GGBF slag and portland cement

Areas of Added Value
GGBF Slag 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

General Applications
- Raw material for the Manufacture of Cement
- Lightweight Fill
- Raw Material for the Manufacture of Glass

Document: Customized Formulation
Environmental Commitment

In the early 1900s, prior to the development of viable construction markets for blast furnace slag, millions of tons were either stockpiled or disposed of by other means.

Though the marketing and research efforts of the National Slag Association’s (NSA) member companies, blast furnace slag has become recognized as the “material of choice” for many construction-related applications, utilizing over thirteen (13) million tons annually in North America.

Steel Slag Coalition

In an attempt to provide industry with a comprehensive environmental assessment of blast furnace slag, the “Steel Slag Coalition” (SSC) was formed in 1995. 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 scientists analyzed samples from each participating company in accordance with EPA’s risk assessment guidelines. The results of this study reinforced 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).

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, man-made resource.