

# Air-Cooled Blast Furnace Slag as Coarse Aggregate in Concrete

An Online Continuing Education Course for Engineers

**Course Number: T-2016**

**Credit: 2 Hours / 2 PDH / 2 CPD**

# Air-Cooled Blast Furnace Slag as Coarse Aggregate in Concrete

## CHAPTER 1. INTRODUCTION

### BACKGROUND

Air-cooled blast furnace slag (ACBFS) has been used as a coarse aggregate in concrete pavements since at least the 1930s. The States of Michigan, Pennsylvania, New York, Indiana, and Ohio, among others, have had considerable experience with ACBFS in concrete pavement construction, with Michigan's usage significantly exceeding that of other highway agencies (Staton 2006). Michigan, in fact, cites extensive use of ACBFS in the Detroit Industrial Expressway system, placed in the 1940s through the 1970s, as well as in many structures of that era and in a number of more recent highway construction projects (Oehler and Finney 1953; Staton 2006). It should be noted that ACBFS can also be used as feedstock for a granulator and the production of slag cement, and thus is a potentially valuable material that should not be considered as "waste."

By definition, blast furnace slag is the nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace. ACBFS is the material resulting from the solidification of molten blast furnace slag in a slag pit under atmospheric conditions with some spraying of water to accelerate cooling so the materials can be moved to the processing plant. Due to a relatively slow rate of cooling, the resulting ACBFS predominately has a crystalline structure, which may contain some glassy and dense particles and which can be crushed to produce an angular and roughly cubical coarse aggregate for use in many aspects of highway construction including use in stabilized and unstabilized base courses, fill and embankments, hot-mix asphalt, and hydraulic cement concrete (simply referred to as concrete in this course).

Two key benefits associated with the use of ACBFS aggregate are resource conservation (reducing the need for natural aggregate) and reduction or elimination of solid waste. Although the environmental considerations are often of primary interest, there are often significant economic benefits as well, since the use of ACBFS aggregate reduces the need for natural aggregate and for landfill disposal (e.g., iron producers financially benefit from the sale of the material while avoiding disposal costs, and ready-mix concrete producers and contractors also financially benefit by obtaining a relatively low-priced reclaimed aggregate compared to natural aggregate materials). These benefits dovetail neatly with the recent focus on sustainability, which has been characterized as a balance between economic, environmental, and societal needs and impacts (Van Dam and Taylor 2009). Thus, the use of ACBFS can help meet sustainability needs in each of those three areas, and therefore can contribute to the sustainability of pavement construction projects provided that overall pavement performance is not compromised.

In that vein, it is important to recognize that ACBFS aggregates are distinct, unique materials, possessing a number of characteristics and properties that must be considered during the design and construction process to ensure long-term performance (Wang and Thompson 2011). For example, ACBFS typically exhibits the following characteristics when compared to natural aggregates (Chesner, Collins, and Mackay 1998; Rao 2006):

- Lower specific gravity.
- Higher porosity and absorption.
- Increased angularity.

Although ACBFS aggregate has been used in concrete pavement construction for more than 80 years, the performance of concrete pavements containing ACBFS has been mixed compared to concrete pavements of similar construction but made with naturally derived aggregates. In Ohio and Indiana, the performance of ACBFS aggregate in paving concrete has been reported to be acceptable. However, in Michigan, the use of ACBFS in paving concrete has been linked to poor performance of concrete pavements (Staton 2006). The Michigan Department of Transportation's (DOT's) pavement management data collected over a period of more than 30 years indicate more frequent repairs and rehabilitation for pavements using concrete with ACBFS aggregate compared to comparable pavements using concrete with natural aggregate. The Michigan DOT data indicate that ACBFS pavements may have a higher life cycle cost over their service life. This varied performance, which has led the Michigan DOT to discontinue the use of ACBFS coarse aggregates in concrete pavements. A number of the potential causes of the observed poor performance have been identified, some of which are linked to unique properties and characteristics of the ACBFS. It is therefore essential that engineers and contractors who use ACBFS in concrete be aware of the unique properties of ACBFS aggregate in order to better assess and predict the long-term performance of pavement structures.

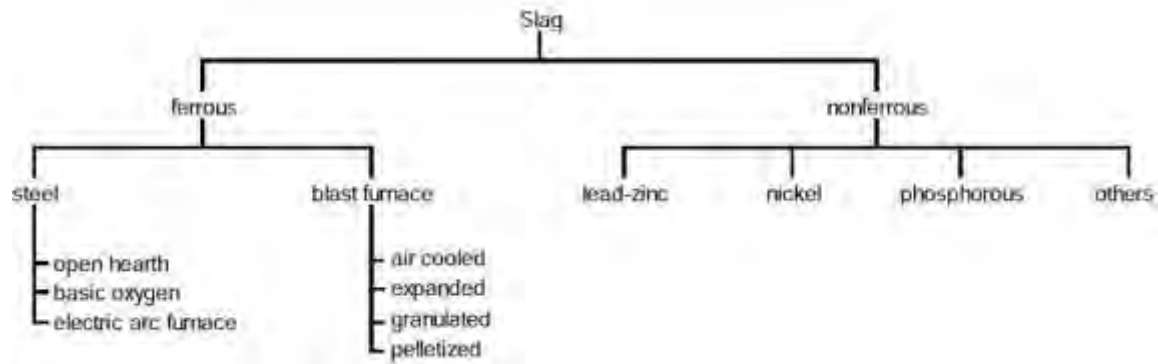
## **CHAPTER 2. ACBFS PRODUCTION AND PROPERTIES**

### **INTRODUCTION**

This chapter describes the production of ACBFS and how that production influences the resultant properties of the material. Typical chemical composition and properties of the ACBFS materials are presented, with emphasis on primary differences that exist between ACBFS aggregate and natural aggregate.

### **TYPES OF SLAG**

Slag is the byproduct of metallurgical operations, typically containing gangue from the metal ore, flux material, and unburned fuel constituents. Slag is often classified into nonferrous and ferrous slags, where nonferrous slags include those derived from copper, lead-zinc, nickel, and phosphorus metallurgical operations, and ferrous slags are those derived from the production of iron and steel. Figure 1 illustrates slag classification based on origin, where ACBFS is shown as a byproduct of the production of pig iron from iron ore (Hammerling 1999).



**Figure 1. Types of slag classified based on origin.**

(From D. M. Hammerling, *Calcium Sulfide in Blastfurnace Slag Used as Concrete Aggregate*, p. 4. © D. M. Hammerling 1999. Adapted with permission.)

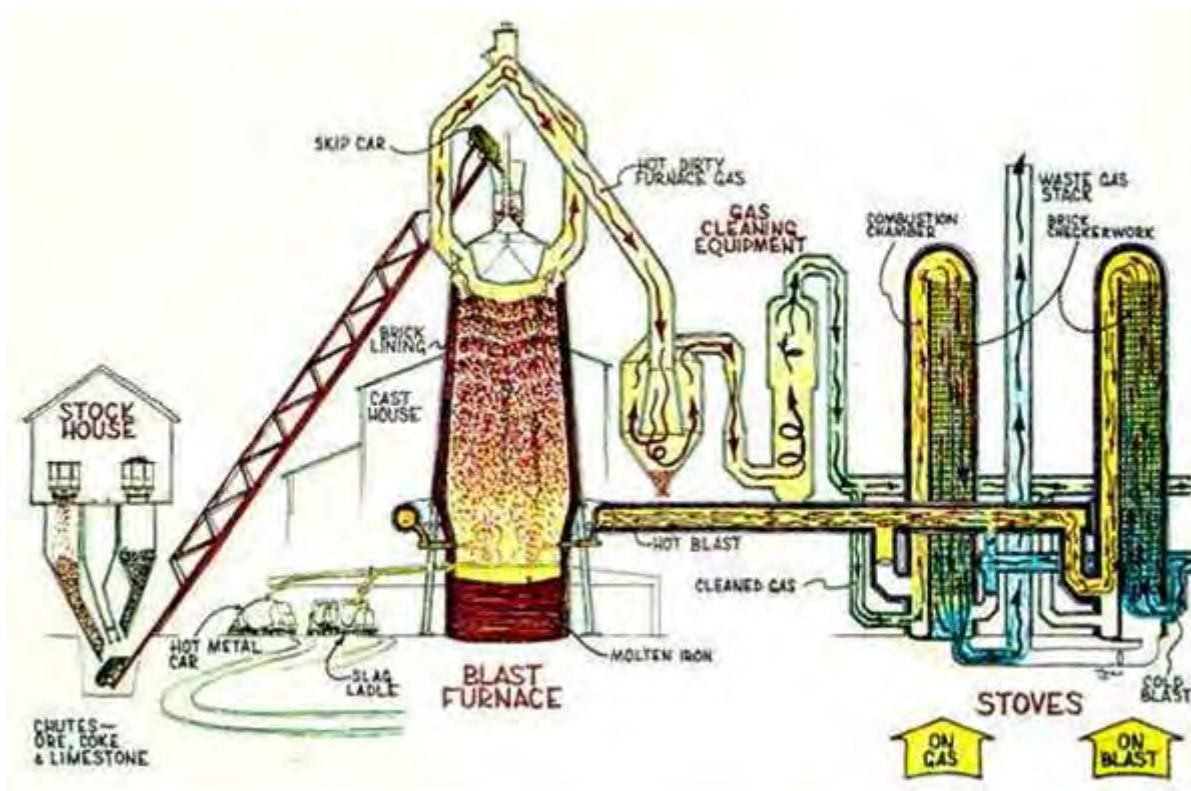
Blast furnace slag is categorized based on how the molten slag is treated once it is removed from the furnace. The primary types of blast furnace slag are the following (Lewis 1982; Chesner, Collins, and Mackay 1998; Pulipaka, Parker, and Kohn 2007):

- ACBFS, which, as previously described, is the material resulting from the solidification of molten blast furnace slag under atmospheric conditions. The molten blast furnace slag is often dumped into a pit, and jets of water are sometimes sprayed onto the slag’s surface to accelerate cooling and facilitate expedited removal of the material so as not to inhibit the smelting process. The final product is then removed from the pit, transported to a crushing and screening facility, and then processed like conventional aggregate, except that magnetic separation is used to remove small pieces of pig iron.
- Expanded (or foamed) blast furnace slag results from the treatment of molten slag with controlled quantities of water (but less than that required for granulation). Expanded slags are more cellular and vesicular than air-cooled slags, and lighter in unit weight.
- Granulated blast furnace slag is created by quickly quenching molten slag with water to produce a glassy, granular product. When crushed or milled to very fine, cement- sized particles, this material has cementitious properties that make it a suitable partial replacement or additive to portland cement.
- Pelletized blast furnace slag is produced when the molten slag is cooled and solidified with water and air quenched in a spinning drum, resulting in the formation of pellets, rather than a solid mass. By controlling the process, the pellets can be made more crystalline, which is beneficial for aggregate use, or more vitrified (glassy), which is more desirable in cementitious applications.

Although some ACBFS may be sprayed with water to expedite processing, such as is done at the Ford Rouge River Complex in Detroit, Michigan, it is still broadly referred to as “air cooled.” The focus of this course is solely on the use of ACBFS as an aggregate in concrete pavements, so the specific production of ACBFS and its inherent properties and characteristics for that application are emphasized from this point forward.

## ACBFS PRODUCTION

In the production of pig iron, the vertical shaft blast furnace is used to smelt iron from iron ore, which contains iron oxide and other minerals, and a fluxing agent (usually limestone, dolomite, or both). The primary fuel is coke, which is subjected to a continuous blast of air, resulting in a high rate of combustion. The fuel, ore, and fluxing agent are supplied continuously through the top of the furnace, while the air is blown into the bottom of the furnace. The smelting process, in which the ore containing iron oxide is converted to metallic iron through a reduction process, occurs as the material moves downward. The end products are the molten metal and the slag, each of which is tapped from the bottom of the blast furnace. Figure 2 presents a schematic of an iron blast furnace.



**Figure 2. Schematic of iron blast furnace.**

(Peacey and Davenport 1979, p. 2, figure 1.1; © Elsevier. Adapted with permission.)

## CHEMICAL AND PHYSICAL PROPERTIES OF ACBFS

### Chemical Composition

As a product of calcinated fluxstone and the alumina and silica phases present in iron ore, the four major oxide phases present in ACBFS are oxides of calcium (CaO), silicon (SiO<sub>2</sub>), aluminum (Al<sub>2</sub>O<sub>3</sub>), and magnesium (MgO). These oxides account for approximately 95 percent of the composition of ACBFS, with the remaining 5 percent consisting of sulfur, manganese, iron, titanium, fluorine, sodium, and potassium, as shown in table 1 (Hammerling 1999). High magnesia content is generally attributed to the use of dolomite as a fluxing agent.

The oxide compositions presented in table 1 are given in weight percentages.

Table 1. Chemical Composition of ACBFS. (Hammerling 1999).

Component	Weight Percentage (%)
Lime (CaO)	95
Silica (SiO <sub>2</sub> )	1-40
Alumina (Al <sub>2</sub> O <sub>3</sub> )	1-42
Magnesia (MgO)	1-22
Minor Components	5
Sulfur (S)	
Iron (Fe)	0.5-1.7
Manganese (Mn)	0.2-1
<i>Rare Components</i>	
Na <sub>2</sub> O + K <sub>2</sub> O	0-1
TiO <sub>2</sub>	0-1
V <sub>2</sub> O <sub>5</sub>	0-1
Cr <sub>2</sub> O <sub>3</sub>	0-1

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