

Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete

Reported by ACI Committee 226



american concrete institute

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Reported by ACI Committee 226

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The use of iron blast-furnace slag as a constituent of concrete, either as an aggregate or as a cementing material, or both, is well known. The use of ground granulated blast-furnace (GGBF) slag in the production of blended cements began in 1905 in the United States. Recent attention has been given to the use of GGBF slag as a separate cementitious constituent of concrete. This report primarily addresses the use of GGBF slag as a separate cementitious material added along with portland cement in the production of concrete. Other slags derived from the smelting of materials other than iron ores are not discussed in this report. The reader should be aware that the material characteristics described and the recommendations for use pertain solely to ground granulated iron blast-furnace (GGBF) slag.

Keywords: blast-furnace slag; concretes; granular materials; iron; mix proportioning; mortars (material); pelleting; portland cements; specifications.

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CHAPTER 1—GENERAL INFORMATION

1.1—History

The use of ground granulated blast furnace (GGBF) slag as a cementitious material dates back to 1774 when Lorient made a mortar using ground blast-furnace slag in combination with slaked lime (Mather 1957).

In 1862, Emil Langen proposed a granulation process to facilitate removal and handling of iron blast-furnace slag leaving the blast furnace. Glassy GGBF slags were later investigated by Michaelis, Prussing, Tetmayer, Prost, Feret, and Green. Their investigation, along with that of Pasow, who introduced the process of air granulation, played an important part in the development of iron blast-furnace slag as a hydraulic binder (Thomas 1979). This development resulted in the first commercial use of slag-lime cements in Germany in 1865. In France, these slag cements were used as early as 1889 to build the Paris underground metro system (Thomas 1979). The use of GGBF slags in the production of blended cements now accounts for nearly 20 percent of the total cement produced in Europe (Hogan and Meusel 1981).

The first recorded production of portland blast-furnace slag cement was in Germany in 1892; the first United States production was in 1896. Until the 1950's, GGBF slag was used in production of cement or as a cementitious material in two basic ways: as a raw material for the manufacture of portland cement, and as a cementitious material combined with portland cement, hydrated lime, gypsum, or anhydrite (Lewis 1981).

Since the late 1950's, use of GGBF slag as a separate cementitious material added at the concrete mixer with portland cement has gained acceptance in South Africa, Australia, the United Kingdom, Japan, Canada, and the United States. Separate grinding of GGBF slag and portland cement, with the materials combined at the mixer, has two advantages over the interground blended cements: 1) each material can be ground to its own optimum fineness and 2) the proportions can be adjusted to suit the particular project needs.

1.2—Scope and objective

This state-of-the-art report presents a detailed discussion of the composition and production of GGBF slag, its use in concrete, and its effects on the properties of concrete.

It is the purpose of this report to review only the properties and use of ground granulated blast furnace slag as a cementitious material added at the concrete mixer along with portland cement. Other types of slag not produced in the iron-making process, (i.e., those derived from the production of copper, lead, and steel) may differ greatly in composition and performance from GGBF slags, and their performance in concrete cannot be predicted from the information provided in this report.

The objective of this report is to compile and present experiences in research and field use of GGBF slag in concrete, and to offer guidance in its selection, proportioning, and use.

1.3—Definitions

Blast-furnace slag—The nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and of other bases, that is developed in a molten condition simultaneously with iron in a blast furnace (ACI 116).

Granulated blast-furnace slag—The glassy granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water (ACI 116).

1.4—Production of blast-furnace slag

In the production of iron, the blast furnace is continuously charged from the top with iron oxide sources (ore, pellets, sinter, etc.), fluxing stone (limestone and dolomite), and fuel (coke). Two products are obtained from the furnace: molten iron that collects in the bottom of the furnace (hearth) and liquid iron blast-furnace slag floating on the pool of iron. Both are periodically tapped from the furnace at a temperature of about 1500 C. The slag consists primarily of silica and alumina (which come from the iron ores), combined with the calcium and magnesium oxides (which come from the fluxing stone). Cementitious activity of this slag for use in mortar or concrete is determined by its composition and the rate at which the molten material is cooled when it comes from the furnace.

1.5—Availability

At the time of this report there were only four sources of GGBF slag in North America. According to the Bureau of Mines, 13,555,000 tons of blast-furnace slag were sold as aggregate in the United States in 1984. This tonnage could be used for the production of cementitious material if granulating facilities were available at all furnace locations. Additional sources of GGBF slag are expected in the future as the costs of production facilities and energy for production of portland cement increase.

1.6—Chemical composition

The composition of blast-furnace slag is determined by that of the ores, fluxing stone, and impurities in the coke charged into the blast-furnace. The **Documents** — silica, alumina, lime, and magnesia — constitute 95 percent or more of the total oxides. Table 1.6 indicates

Table 1.6—Range of chemical composition of blast-furnace slags in the United States and Canada

Chemical constituents (as oxides)	Range of composition, percent by mass
SiO ₂	32 - 40
Al ₂ O ₃	7 - 17
CaO	29 - 42
MgO	8 - 19
S	0.7 - 2.2
Fe ₂ O ₃	0.1 - 1.5
MnO	0.2 - 1.0

the range of chemical analysis of blast-furnace slags produced in the United States and Canada in 1978.

The ranges in composition from source to source shown in Table 1.6 are much greater than those from an individual plant. Modern blast-furnace technology produces very low variability in the compositions of both the iron and the slag from a single source.

To maximize hydraulic (cementitious) properties, the molten slag must be chilled rapidly as it leaves the blast furnace. Rapid "quenching" or chilling minimizes crystallization and converts the molten slag into fine-aggregate-sized particles (generally smaller than a No. 4 sieve), composed of predominantly noncrystalline material. This product is referred to as granulated iron blast-furnace slag. The cementitious action of a granulated blast-furnace slag is dependent to a large extent on the glass content, although other factors will also have some influence. Slowly cooled slags are predominantly crystalline and therefore do not possess significant cementitious properties.

1.7—Processing

Quenching with water is the most common process for granulating slags to be used as cementitious materials. Simple immersion of the molten slag in water was often used in the past; more efficient modern granulation systems use high-pressure water jets that impinge on the stream of molten slag at a water-slag ratio of about 10 to 1 by mass. The blast-furnace slag is quenched almost instantaneously to a temperature below the boiling point of water, producing particles of highly glassy material [Fig. 1.7(a)].

Another process, sometimes referred to as air granulation, involves use of the pelletizer (Cotsworth 1981). In this process, the molten slag passes over a vibrating feed plate, where it is expanded and cooled by water sprays. It then passes onto a rotating, finned drum, which throws it into the air where it rapidly solidifies to spherical pellets. The resulting product may also have high glass content and can be used either as a cementitious material, or in the larger particle sizes, as a lightweight aggregate [Fig. 1.7(b)]. Other processes for combining slag with water used primarily for the production of lightweight aggregates are also capable of producing a sufficiently glassy slag for successful cementitious use (Robertson 1979).

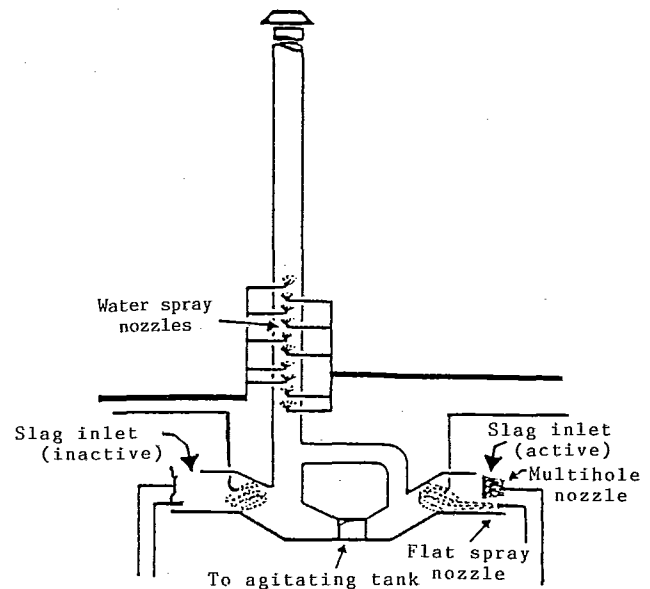


Fig. 1.7(a)—Typical configuration of GGBF-slag water granulator to include steam-condensing tower (Hogan and Meusel 1981)

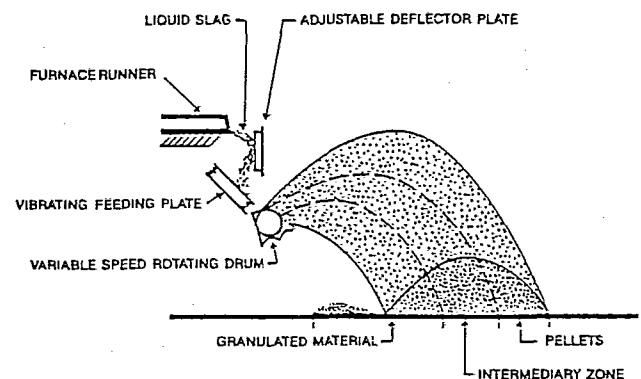


Fig. 1.7(b)—GGBF slag pelletization process, using a minimum of water usually applied at the vibrating feed plate (Hogan and Meusel 1981)

After the granulated blast-furnace slag is formed, it must be dewatered, dried, and ground, using processes similar to those used with portland cement clinker, before it is used as a cementitious material. Magnets are often used before and after grinding to remove residual metallic iron. Typically, the slag is ground to an air-permeability (Blaine) fineness exceeding that of portland cement (i.e., greater than 350 m²/kg) to obtain increased activity at early ages. As with portland cement and pozzolans, the rate of reaction increases with the fineness.

1.8—Specifications

ASTM C 989, adopted in November 1982, provides for three strength grades of GGBF slags, depending on their respective mortar strengths when blended with an equal mass of portland cement. The classifications are

Grades 120, 100, and 80,* based on the slag-activity index expressed as:

- SAI = slag-activity index, percent = $(SP/P \times 100)$
 SP = average compressive strength of slag-reference cement mortar cubes, psi
 P = Average compressive strength of reference cement mortar cubes, psi

Classification is in accordance with Table 1.8 (ASTM C 989) as follows:

Table 1.8—Slag-activity index standards for various grades as prescribed in ASTM C 989

Age and Grade	Slag-activity index, minimum percent	
	Average of last five consecutive samples	Any individual sample
7-day index		
Grade 80	—	—
Grade 100	75	70
Grade 120	95	90
28-day index		
Grade 80	75	70
Grade 100	95	90
Grade 120	115	110

The slag-activity index test is influenced by the portland cement used; ASTM C 989 specifies total alkalis and 28-day compressive strengths for the reference cement. The precision of this test is such that the coefficient of variation is 4.1 percent for single laboratory testing and 5.7 percent for multilaboratory testing.

In addition to requirements on strength performance, the specification limits the residue on a 45- μ m (No. 325) sieve to 20 percent and the air content of a

mortar containing only GGBF slag to a maximum of 12 percent.

The specification also includes two chemical requirements: one limiting the sulfide sulfur (S) to a maximum of 2.5 percent and the other limiting the sulfate content (reported as SO_3) to a maximum of 4.0 percent.

Canadian standards CSA A 363, "Cementitious Hydraulic Slag," and CSA A 23.5, "Supplemental Cementing Materials and Their Use in Concrete Construction," differentiate between GGBF slags that react hydraulically with water and those that require activators to develop their cementitious properties quickly.

Blended cements, in which the GGBF slags are combined with portland cement, are covered by ASTM C 595. Three types of such cements are addressed: 1) slag-modified portland cement (Type I [SM]), in which the GGBF slag constituent is less than 25 percent of the total weight; 2) portland blast-furnace slag cement (Type IS), which contains 25 to 70 percent GGBF slag; and 3) slag cement (Type S), containing 70 percent or more GGBF slag. While the specifications permit the GGBF slag and the other ingredients to be ground either together or separately and blended, most portland blast-furnace slag cements have been interground. Such cements have been used worldwide for almost 100 years, and have excellent service records (Lea 1971).

1.9—Hydraulic reactivity

There is general agreement among researchers (Smolczyk 1978) that the hydration product that is formed when GGBF slag is mixed with portland cement and water is essentially the same as the principal product formed when portland cement hydrates, i.e., calcium-silicate hydrate (CSH) (Smolczyk 1978). As seen in the ternary diagram in Fig. 1.9(a), portland cement and GGBF slag lie in the same general field, although portland cement is essentially in the C_3S field whereas GGBF slag is found essentially in the C_2S field of the diagram. GGBF slag hydrates are generally found to be more gel-like than the products of hydration of portland cement, and so add denseness to the cement paste.

In the hydration of portland cement, the tricalcium aluminate phase reacts instantly upon adding water, and the sulfate and hydroxyl ions activate the subsequent hydration of both calcium silicates, alite, and belite.

When GGBF slag is mixed with water, initial hydration is much slower than portland cement mixed with water; therefore, portland cement or alkali salts are used to increase the reaction rate. Hydration of GGBF slag in the presence of portland cement depends largely upon breakdown and dissolution of the glassy slag structure by hydroxyl ions released during the hydration of the portland cement. The hydration of the GGBF slag consumes calcium hydroxide and uses it for additional calcium silicate hydrate formation.

Recent research (Regourd 1980) shows that a very small immediate reaction also takes place when GGBF slag is mixed with water, preferentially releasing calcium and aluminum ions to solution. The reaction is

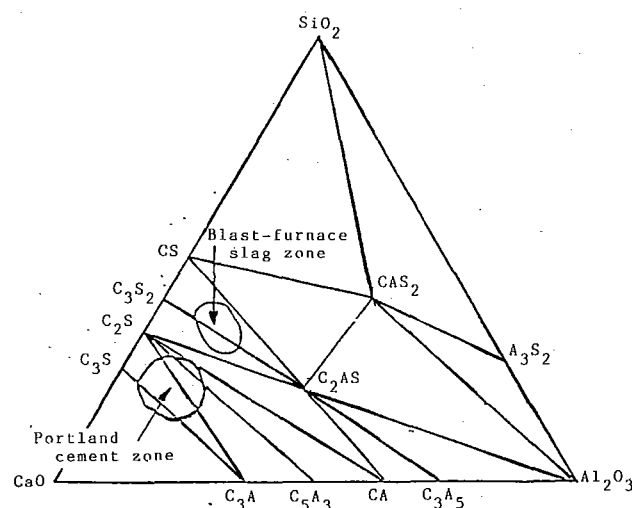


Fig. 1.9(a)—Ternary diagram indicating composition of portland cement and GGBF slag in the system $CaO-SiO_2-Al_2O_3$ [based on Lea (1971) and Bakker (1983)]

*The literature referenced in this report does not always identify the slag by grade because the standard for grade determination was not recognized prior to 1982.