

ACI 233R-17

Guide to the Use of Slag Cement in Concrete and Mortar

Reported by ACI Committee 233



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Guide to the Use of Slag Cement in Concrete and Mortar

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Guide to the Use of Slag Cement in Concrete and Mortar

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This report addresses the use of slag cement as a separate cementitious material added along with portland cement in the production of concrete. This report does not address slags derived from the smelting of materials other than iron ores. The material characteristics described and the recommendations for its use pertain solely to cement ground from granulated iron blast-furnace slag.

Keywords: blast-furnace slag; cementitious material; granulated blast-furnace slag; hydraulic cement; mixture proportion; mortar; portland cement; slag cement.

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CHAPTER 1—GENERAL INFORMATION

1.1—History

The use of slag cement as a cementitious material dates back to 1774, when a mortar was made using slag cement in combination with slaked lime (Mather 1957). In 1862, a granulation process was proposed to facilitate removal and handling of iron blast-furnace slag leaving the blast furnace. The use of granulation produced glassy material that 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).

Mary (1951) described the preparation of slag cement by the Trief wet-process and its use in the Bort-les-Orgues Dam. This was done after World War II when the supply of portland cement was limited. The dam involved 660,000 m³ (863,000 yd³) of concrete. The slag was ground wet and charged into the mixer as a thick slurry.

A sample of the Trief wet-process cement was obtained by the Corps of Engineers in December 1950 and tested at the Waterways Experiment Station (WES) (1953). In the WES tests, the behavior of the ground slag from Europe was compared with slag ground in the laboratory from expanded slag from Birmingham, AL. Each slag was activated with 1.5 percent sodium hydroxide and 1.5 percent sodium chloride by mass, with generally similar results.

In the former Soviet Union and several European countries, the use of slag cement in alkali-activated systems where no portland cement is used has been found to provide special properties (Talling and Brandstetr 1989).

The first recorded production of blended cement in which blast-furnace slag was combined with portland cement was in Germany in 1892; the first United States production was in 1896. By 1980, the use of slag cement in the production of blended cement accounted for nearly 20 percent of the total hydraulic cement produced in Europe (Hogan and Meusel 1981).

Until the 1950s, slag cement was used 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 1950s, use of slag cement 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, among other countries.

In 2000, production capacity for slag cement was estimated to exceed 2,000,000 metric tons or Megagrams (Mg) annually in North America. In the United States, production of slag cement was estimated to exceed 1,500,000 Mg, up from approximately 700,000 Mg in 1990.

cement and granules are also being imported from various countries into the United States.

According to [Van Oss \(2015\)](#), 7,600,000 Mg of iron blast-furnace slag was produced in the United States in 2013; 2,300,000 Mg of that being granulated, and 5,300,000 Mg air-cooled. According to the Slag Cement Association, 2,500,000 Mg of slag cement and 540,000 Mg of slag blended cement were used in concrete and other construction applications (some of which used imported granules). More sources of slag cement may become available due to energy and environmental stimuli.

The majority of slag cement in the United States is batched as a separate ingredient at concrete production plants. Approximately 9 percent, however, is used to produce blended hydraulic cements. Slag cement is also used for other applications, including stabilizing mine tailings and industrial waste.

1.2—Scope and objective

The objective of this report is to compile and to present experiences in research and field use of slag cement in concrete and mortar, and to offer guidance in its specification, proportioning, and use. Presented is a detailed discussion of the composition and production of slag cement, its use, and its effects on the properties of concrete and mortar. Slags from the production of metals other than iron differ greatly in composition from slag cement and are not within the scope of this report.

1.3—Environmental considerations

The use of slag cement in concrete and mortar is an environmentally sound and efficient use of existing resources. Slag cement offers several benefits when used to replace a portion of the portland cement, including reduced energy consumption, reduced greenhouse gas emissions, and reduced consumption of virgin raw materials. For a more complete discussion on sustainability, refer to [Chapter 9](#).

1.4—Production

1.4.1 Origin of blast-furnace slag—In the production of iron, the blast furnace is continuously charged from the top with iron oxide (ore, pellets, and sinter), fluxing stone (limestone or 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 molten iron. Both are periodically tapped from the furnace at a temperature of approximately 2700°F (1500°C).

1.4.2 Granulated slag—Quenching with water is the most common process for production of granulated slag to be used as a cementitious material. Simple immersion of the molten slag in water was often used in the past. This quenching method is sometimes called the pit process. More efficient modern granulation systems use high-pressure water jets that impinge on the stream of molten slag at a water-slag ratio of approximately 10 to 1 by mass. In this quenching method, called jet process granulation, the blast-furnace slag is quenched almost instantaneously to a temperature below

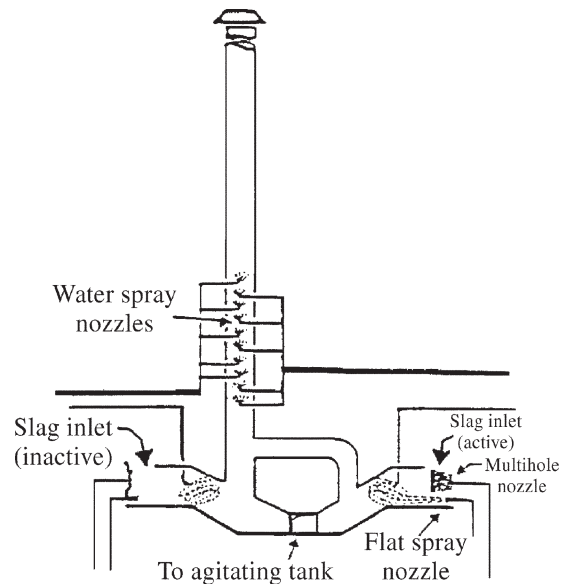


Fig. 1.4.2a—Configuration of blast-furnace slag water granulator to include steam-condensing tower (Hogan and Meusel 1981).

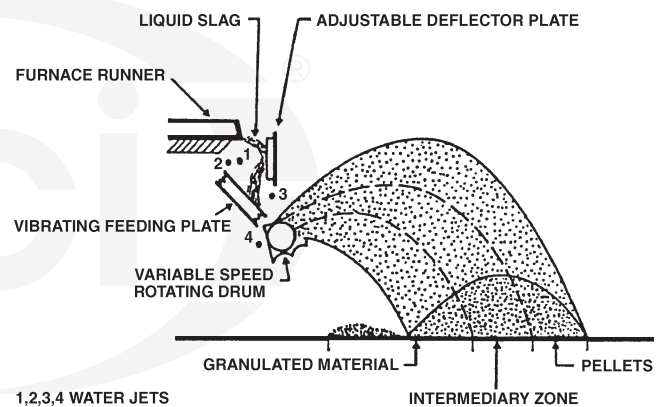


Fig. 1.4.2b—Blast-furnace slag palletization process, using a minimum of water usually applied at the feed plate (Hogan and Meusel 1981).

the boiling point of water, producing slag particles with high glass content. This material is called granulated blast-furnace slag (GBFS) or slag granules. A close-up view of the part of a jet-process granulator system where the water meets the molten blast-furnace slag is shown in Fig. 1.4.2a.

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 the slag into the air where it rapidly solidifies to spherical pellets (Fig. 1.4.2b). The resulting product may also have a high glass content and can be used either as a cementitious material or, in the larger particle sizes, as a lightweight aggregate. Other processes for combining slag with water, which are used primarily for the production of lightweight aggregates, are also capable of producing a sufficiently glassy slag for use as a cementitious material ([Robertson 1982](#)).

1.4.3 Slag cement—Granules are dewatered and ground before they are used as a cementitious material. Often, some, or all, of the granules are dried with heaters before milling. Magnets are often used before and after grinding to remove residual metallic iron. For increased cementitious activity at early ages, the ground slag, referred to as slag cement, is typically ground finer than portland cement. As with portland cement and pozzolans, the rate of reaction increases with the fineness.

1.4.4 Blended cements—Slag cement or slag granules can be used to produce portland blast-furnace slag cement. Slag granules and portland cement clinker can be interground to a combined target fineness, or the two materials can be ground separately to individual target fineness before blending or a combination of intergrinding and blending.

CHAPTER 2—DEFINITIONS

2.1—Definitions

air-cooled blast-furnace slag—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.

blast-furnace slag—nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and of other bases, that develops in a molten condition simultaneously with iron in a blast furnace.

blended cement—hydraulic cement consisting of portland cement uniformly mixed with slag cement or pozzolan, or both.

glass—inorganic product of fusion, which has cooled to a rigid condition without crystallization.

portland blast-furnace slag cement—a hydraulic cement consisting of an intimately interground mixture of portland-cement clinker and granulated blast-furnace slag or an intimate and uniform blend of portland cement and fine granulated blast-furnace slag in which the amount of the slag constituent is within specified limits.

slag cement—granulated blast-furnace slag that has been finely ground and is a hydraulic cement.

CHAPTER 3—PROPERTIES AND PRODUCT TYPES

3.1—Chemical and physical properties

The chemical composition of blast-furnace slag is determined by that of the ore, fluxing stone, and impurities in the coke charged into the blast furnace. Typically, silica, calcium, aluminum, magnesium, and oxygen constitute 95 percent or more of the blast-furnace slag. Table 3.1 indicates the chemical analysis range for major elements (reported as oxides) in blast-furnace slag produced in the United States and Canada in 1988.

The ranges in composition from source to source shown in Table 3.1 are much greater than those from an individual plant. Modern blast-furnace technology typically produces low variability in the compositions of both the iron and the slag from a single source.

Table 3.1—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 to 42
Al ₂ O ₃	7 to 16
CaO	32 to 45
MgO	5 to 15
S	0.7 to 2.2
Fe ₂ O ₃	0.1 to 1.5
MnO	0.2 to 1.0

*Except for sulfur.

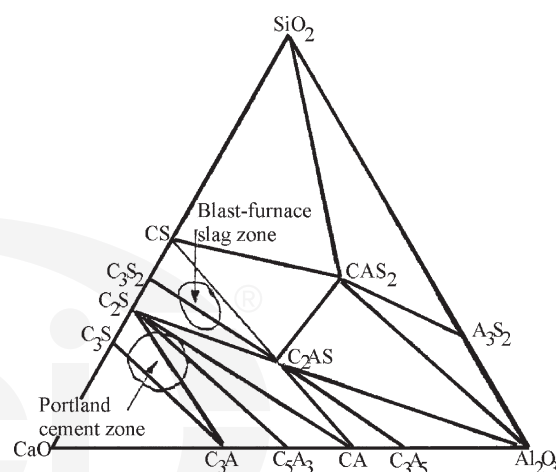


Fig. 3.2a—Phase diagram indicating composition of portland cement and blast-furnace slag in the system CaO-SiO₂-Al₂O₃ (based on Lea [1971] and Bakker [1983]).

To maximize cementitious properties, the molten slag should 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 passing a No. 4 (4.75 mm) sieve, composed predominantly of glass. This product is referred to as granulated blast-furnace slag (referred to herein as granules). The potential activity of granules depends largely on the chemistry and the glass content. Glass content is often associated with cementitious activity when ground. Other factors will also have some influence. Slowly cooled slag, such as air-cooled blast-furnace slag, is predominately crystalline and therefore does not possess significant cementitious properties when ground.

3.2—Hydraulic activity

There is general agreement among researchers (Smoleczyk 1978) that the principal hydration product that is formed when slag cement is mixed with portland cement and water is essentially the same as the principal product formed when portland cement hydrates, that is, calcium-silicate-hydrate (C-S-H). As seen in the phase diagram in Fig. 3.2a, portland cement and slag cement lie in the same general field, although slag cement has a higher silica content.

When slag cement is mixed alone with water, initial hydration is much slower than that of portland cement; therefore, portland cement, alkali salts, or lime are used to increase the reaction rate. Hydration of slag cement 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.

When slag cement hydrates, it reacts with sodium and potassium alkali and calcium hydroxide (Ca(OH)_2) to produce additional C-S-H. Regourd (1980a,b, 1983) showed that a small immediate reaction also takes place when slag cement is mixed with water, preferentially releasing calcium and aluminum ions to solution. The reaction is limited, however, until additional alkali, calcium hydroxide, or sulfates are available for reaction.

Research by Regourd (1980a,b, 1983), Vanden Bosch (1980), and Roy and Idorn (1982) suggests that the hydration of slag cement in combination with portland cement at normal temperature is a two-stage reaction. From initial wetting through early hydration, the predominant reaction is with alkali hydroxide, but subsequent reaction is predominantly with calcium hydroxide. Calorimetric studies of the rate of heat liberation show this two-stage effect, in which the major amount of slag cement hydration lags behind that of the portland cement component (Fig. 3.2b).

With increasing temperature, the alkali hydroxides from the cement have greater solubility; therefore, they predominate in promoting the early reactions of the slag cement. The contribution of slag cement to early-age strength is more significant at high curing temperatures, such as those that occur in large structural elements, than the standard curing regimes adopted for companion cubes (Barnett et al. 2007). Forss (1982) and Voinovitch et al. (1980) have shown that alkali hydroxide alone—that is, without calcium hydroxide from portland cement hydration—can hydrate slag cement to form a strong cement paste structure, which may be used in special applications such as soil stabilization and alkali-activated concrete.

Considerable research has been conducted on using alkali-activated slag cement as the sole binder in mortar and concrete, eliminating the need for portland cement (Pacheco-Torgal et al. 2008a,b). Alkali-activated slag cement was patented in 1958. A review given by Glukhovskiy et al. (1980) commented that alkali-activated slag cements had been introduced into construction practice in the U.S.S.R. in 1960 and in Poland in 1972. Alkali-activated slag cements have been employed on a limited scale as oil well cements and in mine applications in South Africa and Canada. Precast products have used these cements in Eastern Europe, Finland, and France (Talling and Brandstetr 1989).

3.3—Factors determining cementitious properties

A discussion of the basic principles of slag cement hydration makes it possible to identify the primary factors that, in practice, will influence the effectiveness of the uses of slag cement in concrete and mortar. These factors are:

a) Chemical composition of the slag cement and portland cement

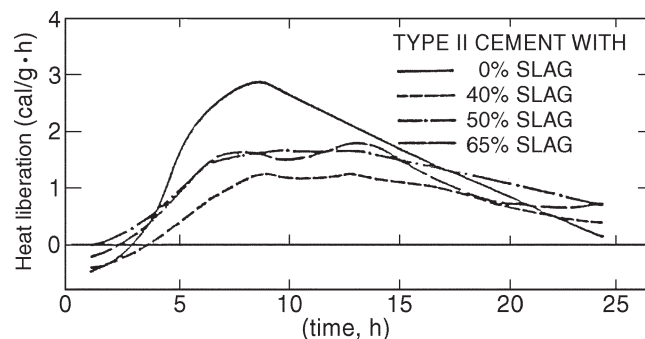


Fig. 3.2b—Rate of heat liberation of cements with and without slag cement at 80°F (27°C) (Roy and Idorn 1982).

- b) Alkali ion concentration in the reacting system
- c) Glass content of the slag cement
- d) Fineness of the slag cement and the portland cement
- e) Temperature during the early phases of the hydration process

Due to the complexity of the influencing factors, it is not surprising that earlier attempts to relate the hydration of slag cement to simplified chemical models failed to provide adequate evaluation criteria (Mather 1957; Hooton and Emery 1980). The complexity of the reacting system suggests that direct performance evaluations of workability, strength characteristics, and durability are the most satisfactory measures of the effectiveness of the use of slag cement in concrete and mortar. The ASTM C989/C989M slag-activity index is often used as a basic criterion for evaluating the relative cementitious potential of a slag cement. Furthermore, proportioning for specific performance requirements should be based on tests of concrete, including the same materials intended to be used in the work.

3.4—Slag cement

3.4.1 Types—ASTM C989/C989M, first adopted in 1982, designates three strength grades of slag cements. The grade depends on the mortar strength of a slag-portland cement mortar relative to that of a reference portland cement mortar. The portland cement used influences the slag-activity index test. ASTM C989/C989M specifies total alkali limits and 28-day compressive strengths for the reference cement.

Slag cement is classified as Grade 120, Grade 100, and Grade 80, based on a slag-activity index expressed as:

- a) $\text{SAI} = \text{slag-activity index, percent} = (\text{SP}/\text{P}) \times 100$
- b) SP = average compressive strength of the 50:50 slag-reference portland cement mortar cubes, psi (MPa)
- c) P = average compressive strength of reference cement mortar cubes, psi (MPa)

Classification can be found in Table 3.4.1 (adapted from ASTM C989/C989M). In addition to requirements on strength performance, ASTM C989/C989M limits the residue on a No. 325 (45 micron) sieve to 20 percent and the air content to a maximum of 12 percent.

The specification also limits the sulfide sulfur (S) to a maximum of 2.5 percent. In Canada, CSA A3001 only defines one type of slag cement, which is an ASTM minimum 28-day strength activity index of 80 percent.

Table 3.4.1—Slag activity index standards for various grades as prescribed in ASTM C989/C989M

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

3.5—Blended cements

Blended cements, which include slag cements and other ingredients, have been used for over 100 years and have an excellent service record (Lea 1971). ASTM C595/C595M covers blended cements. Prior to 2007, three types of such cements were addressed: 1) slag-modified portland cement [Type I (SM)], which contains less than 25 percent slag cement; 2) portland blast-furnace slag cement (Type IS), which contains 25 to 70 percent slag cement; and 3) slag cement (Type S), which contains 70 percent or more slag cement. In 2007, these three types were consolidated into one, Type IS(X)-portland blast-furnace slag cement, where (X) equals the targeted percentage of slag in the product. In 2009, ASTM C595/C595M added Type IT(X)(Y) for ternary systems, where Y equals the targeted percentage of another constituent material.

ASTM C1157/C1157M was issued in 1992 as the first performance specification for hydraulic cements, and it features six blended cement types. Granules or slag cement may be used as a component in the production of ASTM C1157/C1157M cement. Ternary systems may also be produced under ASTM C1157/C1157M.

CSA A3001 allows blends of up to three supplementary cementing materials (SCMs). The specification requires that the percent of each be indicated in the nomenclature of the blended material. Blended products are also classified according to the performance characteristics of the final blended material (that is, sulfate-resistant and low-heat).

CHAPTER 4—STORAGE, HANDLING, AND BATCHING

4.1—Storage

As is the case with portland cement and most supplementary cementitious materials (SCMs), slag cement should be stored in bins or silos to provide protection from dampness and contamination. Color and fineness of slag cement can be similar to those of portland cement; therefore, necessary precautions should be taken to clearly mark handling and storage equipment. When compartmented bins are used, periodic checks for leaks between adjacent bins should be conducted to avoid contamination of the stored materials.

4.2—Handling

Slag cement is handled with the same kinds of equipment as portland cement and other SCMs. The most commonly

used pieces of equipment are pneumatic pumps, screw conveyors, air slides, and bucket elevators. Unlike some other finely divided materials that are extremely fluid when aerated, slag cements do not require special gates or feeders.

4.3—Batching

Slag cement should be batched by mass as required by ASTM C94/C94M. These recommendations are applicable to slag cement and other SCMs that are introduced separately to the batch and not those concretes that contain ASTM C595/C595M blended cements. Based on industry experience, the following batch sequences are typically used. In binary systems, where slag cement is batched cumulatively in the same weigh hopper with portland cement, the slag cement should follow the batching of portland cement to ensure that the required mass of portland cement is obtained. For ternary systems containing fly ash and most other SCMs, slag cement should follow portland cement and precede the addition of fly ash and the other SCMs. For ternary systems containing silica fume, depending on the type of silica fume used, it is sometimes recommended that it be introduced into the empty mixer, and in those cases, slag cement should follow portland cement as in a binary system. Additional information is available in ACI 234R. With the aforementioned exception, when the slag cement is introduced into the mixer, it is preferable to introduce it simultaneously with the other components of the concrete mixture.

CHAPTER 5—PROPORTIONING CONCRETE CONTAINING SLAG CEMENT

5.1—Proportioning with slag cement

The proportion of slag cement in a concrete mixture will depend on the purposes for which the concrete is to be used, the curing temperature, the grade (activity) of the slag cement, and the portland cement or other activator. In most cases, slag cements have been used in proportions of 25 to 80 percent by mass of the total cementitious material. For applications using a binary system of portland and slag cement, typical slag replacement rates are given in Table 5.1 (Slag Cement Association 2009).

In binary cementitious systems, the optimum percentage of slag cement that provides the highest compressive strength at 28 days is usually 40 to 50 percent by mass of the total cementitious material, although this relationship varies depending on the grade of slag cement and other considerations (Hogan and Meusel 1981; Fulton 1974).

Some other considerations that may determine the proportion of slag cement include the requirements for permeability and chloride resistance, temperature rise control, time of setting and finishing, sulfate resistance, and the control of expansion due to the alkali-silica reaction (ASR). For example, where high sulfate resistance is required, the slag cement content should be at least 50 percent by mass of total cementitious material, unless previous testing with a specific slag cement and local materials has indicated that a lower percentage is adequate (Chojnacki 1981; Hogan and Meusel 1981; Fulton 1974; Lea 1971; Hogan and Emery 1990).

Table 5.1—Typical replacement rates for portland cement by mass

Concrete application	Slag cement
Concrete paving	25 to 50 percent
Exterior flatwork not exposed to deicer salts	25 to 50 percent
Exterior flatwork exposed to deicer salts with $w/cm < 0.45$	25 to 50 percent
Interior flatwork	25 to 50 percent
Basement floors	25 to 50 percent
Footings	30 to 65 percent
Walls and columns	25 to 50 percent
Tilt-up panels	20 to 50 percent
Prestressed concrete	20 to 50 percent
Precast concrete	20 to 50 percent
Concrete blocks	20 to 50 percent
Concrete pavers	20 to 50 percent
High strength	25 to 50 percent
Alkali-silica reaction mitigation	25 to 70 percent
Sulfate resistance	
Type II equivalence	25 to 50 percent
Type V equivalence	35 to 65 percent
Lower permeability	25 to 65 percent
Mass concrete	50 to 80 percent
Percentages indicate replacement for portland cement by mass. These replacement rates are for individual applications and are based on historical performance. Variations in material sources and environmental conditions may require alternate substitution rates. Testing should be done with local project materials to verify intended performance.	

Where slag cements are blended with portland cement, the combination of cementitious materials will result in physical properties that are characteristic of the predominant material. For example, as the percentage of slag cement increases, a slower rate of strength gain should be expected, particularly at early ages, unless the water content is substantially reduced, chemical accelerators are used, accelerated curing is provided, or it is mass concrete.

The proportioning techniques for concrete incorporating slag cements are similar to those used in proportioning concrete made with portland cement or blended cement. Methods for proportioning are given in [ACI 211.1](#). Adjustments should be made for changes in solid volume due to the difference in relative density (specific gravity) of slag cement (2.85 to 2.94) and portland cement (3.15).

While the difference in absolute volume of the cementitious paste is minimal with regard to the yield of concrete, it can influence the finishing characteristics of the concrete, depending on the proportions of the slag cement and the total cementitious material in the concrete mixture. In lean mixtures, the additional cementitious material improves finishing characteristics. In concrete mixtures containing high cementitious materials, the concrete may be sticky and have poor finishability. This is normally addressed in the

proportioning of the concrete mixture by adjusting the ratio of coarse to fine aggregate or adjusting the type or dosage of chemical admixtures.

Typically, concrete with slag cement is easier to place and consolidate; hence, greater functional volumes of coarse aggregate may be used to reduce water demand and drying shrinkage. Often, an increase in coarse aggregate is desirable because it often reduces the stickiness of concrete mixtures ([Wood 1981](#); [Fulton 1974](#)). This is particularly true when high cement contents are used. Slag cement can be used in self consolidating concrete (SCC) using roughly the same replacement percentages as with other concrete. The fineness of slag cement helps to provide improved flow when compared to concrete without slag cement. Because SCC mixtures typically have high cementitious and low water contents, with the slower-setting characteristics of high replacement levels of slag cement, the use of slag cement can help increase the available time for placement.

Slag cement is usually substituted for portland cement on a one-to-one basis by mass and is always included in the determination of the water-cementitious materials ratio (w/cm).

Water demand for given slump may be 3 to 5 percent lower in concrete containing slag cement than that found with concrete without slag cements, depending on the replacement level and other factors ([Meusel and Rose 1983](#)). Exceptions may be found, and these should be identified in the trial mixture proportioning studies. The degree of water reduction will depend on the amount of slag cement used, aggregate properties, and other characteristics of the mixture. This variability, if evident, may be minimized by changes to the aggregate proportions or changing the type, dosage of chemical admixtures, or both.

5.2—Ternary systems

The use of slag cement in combination with portland cement and pozzolans, such as fly ash and silica fume, is not uncommon. Ternary systems may be achieved by using preblended cement products, materials added individually at the batch plant, or a combination of the two. The use of a ternary system may have some economic benefits, but it is generally used for improving engineering properties.

Combinations of slag cement, portland cement, and silica fume were used in concrete mixtures in high-strength applications for the Scotia Plaza in Toronto (28 percent slag cement + 7.5 percent silica fume) ([Aïtcin and Neville 1993](#)) and Society Tower (now Key Tower) in Cleveland, OH (29 percent slag cement + 12 percent silica fume) ([Engineering News Record 1991](#)). Similar combinations were used in the Shepherd Subway precast tunnel liners (25 percent slag + 8 percent silica fume), the columns of BCE Tower (25 percent slag cement + 10 percent silica fume blended cement), and the bridges and decks at the Pearson Airport (25 percent slag cement + 8 percent silica fume), all in Toronto ([Bouzoubaa and Foo 2005](#)). Combinations of slag cement, fly ash, and portland cement were used in support columns for the retractable roof at Reliant Stadium in Houston, TX (30 percent slag cement + 20 percent fly ash), where low water demand and high compressive strength were desired ([Slag Cement Asso-](#)

ciation 2002b). In addition, the combination of slag cement, fly ash, and portland cement appears to be the most appropriate binding material for the solidification and stabilization of low-level nuclear waste forms (Langton 1989; Spence et al. 1989).

The Ohio Department of Transportation (1994) has used high-performance concrete containing portland cement with 30 percent slag cement, 4.5 percent silica fume, and a 0.38 w/cm for the construction of bridge decks. In 2002, the Iowa Department of Transportation used 35 percent slag cement and 15 percent fly ash mixtures for high-performance concrete in the reconstruction of bridges on the I-235 loop around Des Moines (Dunker 2003). The Federal Aviation Administration (2014) allows the use of slag cement with fly ash. Beginning in 1997, mainline pavements have featured combinations of portland cement with slag cement and fly ash in Iowa, Minnesota, and Wisconsin.

Concrete mixtures that use a cementitious system of portland cement, slag cement, and fly ash are increasingly being used in the United States in general-use concrete. These mixtures typically have a portland cement content of 50 percent and the other 50 percent is made up of various blends of slag cement and fly ash. Most common are systems containing 50 percent portland cement, 30 to 35 percent slag cement, and 15 to 20 percent fly ash. Trial batches should be performed to determine the proportions for a given set of materials.

Silica fume can be added to ternary or other cementitious systems to promote increased strength and reduced permeability at early ages. Silica fume dosages are typically the same or less as when used in concrete without slag cement. In most cases, using slag cement and silica fume together can reduce the required cement replacement levels for a given level of durability performance. Additional information on the use of silica fume is available in ACI 234R.

In high-pressure steam (356°F [180°C]) autoclaved concrete masonry, slag cement has been used in combination with portland cement and ground quartz (silica flour) (Hooton and Emery 1980). At lower temperatures, however, ground quartz may not be reactive enough to be considered a cementitious material.

5.3—Use with chemical admixtures

Effects of chemical admixtures on the properties of concrete containing slag cement are similar to those for concrete made with portland cement as the only cementitious material. Information regarding the effect of admixtures on the properties of concrete can be found in ACI 212.3R. Small adjustments in the dosage rate of air-entraining admixtures are sometimes necessary, depending on the fineness and replacement level of the slag cement. Slag cement concrete may require a slightly higher dosage rate of air-entraining admixture to achieve a given air content. In most cases, slag cement concrete will require a slightly lower dosage of water-reducing admixtures. Likewise, the dosage of high-range water-reducing admixtures (HRWRAs) required to produce flowing concrete is usually less than that used in concrete not containing slag cement (Wu and Roy 1982).

When dosing retarding admixtures based on the total cementitious material, a given amount of retarder will have a greater retarding effect as the proportion of slag cement in the concrete is increased. The increased retardation is particularly noticeable with portland cements having low C_3A and alkali levels. Other chemical admixtures such as accelerators, corrosion inhibitors, shrinkage-reducing admixtures, viscosity-modifying admixtures, and others can also be used in concrete containing slag cement.

CHAPTER 6—EFFECTS ON PROPERTIES OF FRESH CONCRETE

6.1—Workability

Fulton (1974) investigated workability of concrete in great detail and suggested that a cementitious matrix containing slag cements exhibited greater workability due to the increased paste content and increased cohesiveness of the paste. Wood (1981) reported that the workability and placeability of fresh concrete containing slag cement was improved when compared with concrete containing no slag cement. He further stated that this result was due to the surface characteristics of the slag cement, which created smooth slip planes in the paste. He also theorized that, due to the smooth, dense surfaces of the slag cement particles, the slag cement absorbed little, if any, water during initial mixing, unlike portland cement. Wu and Roy (1982) found that pastes containing slag cements exhibited different rheological properties compared with pastes of portland cements alone. Their results indicate a better particle dispersion and higher fluidity of the pastes and mortars, both with and without water-reducing admixtures.

Concrete containing slag cement is consolidated under mechanical vibration more easily than concrete that does not contain slag cement (Fig. 6.1a). Considering his earlier findings, Fulton (1974) devised a test using the Vebe apparatus in which unconsolidated concrete was molded by vibration, and differences in molding time of mixtures with and without slag cement were compared. In all cases, the consolidation of the concrete containing 50 percent slag cement was superior to that of mixtures without slag cement. Meusel and Rose (1983) found that increased slump was obtained with all slag cement blends tested when compared with concrete without slag cement at the same water content (Fig. 6.1b). Osborne (1989) presented results of slump, Vebe, and compacting factor tests for concrete containing 0, 40, and 70 percent slag cement. The tests showed that as the percentage of slag cement increased, the w/cm had to be reduced to maintain workability properties similar to the concrete with no slag cement. Wimpenny et al. (1989) found that in concrete with constant w/cm , the slump increased significantly with increasing slag cement replacement.

6.2—Time of setting

Using the ASTM C403/C403M penetration resistance test, Luther and Mikols (1993) showed that the time of setting of concrete made with 40 percent slag cement was not affected by slag cement fineness over the range of 400 to 1400 m^2/m^2 .

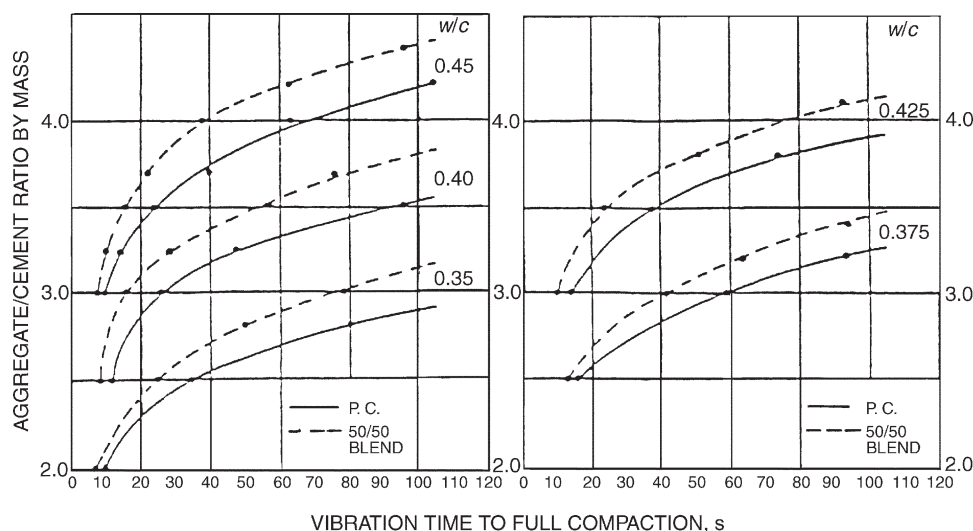


Fig. 6.1a—Relationship between response to vibration of concrete mixtures made with portland cement and mixtures containing 50 percent slag cement (Fulton 1974).

kg range (Blaine fineness). Luther et al. (1994) presented information indicating that at approximately 70°F (21°C), the setting time was increased by 1 hour at 35 to 40 percent replacement, and an increase in slag cement replacement of portland cement increased setting time. Together, this information suggests that the portland cement setting characteristics and the amount of portland cement are significant factors in controlling the setting time of concrete containing slag cement.

Delays in setting time can be expected when more than 25 percent slag cement is used as a replacement for portland cement in concrete mixtures. The degree to which the setting time is affected depends on the temperature of the concrete, the percentage of portland cement replaced by slag cement, the w/cm , and the characteristics of the portland cement (Fulton 1974). The admixture type and dosage as well as the amount of portland cement are also important. Hogan and Meusel (1981) found that for 50 percent slag cement, the initial setting time is increased 1/2 to 1 hour at 73°F (23°C); little if any change was found above 85°F (29°C).

Although significant retardation has been observed at low temperatures, addition of conventional accelerators, such as calcium chloride or nonchloride accelerating admixtures, can reduce or eliminate this effect. Because the amount of portland cement in a mixture usually determines setting characteristics, reducing the slag cement-portland cement ratio may be considered in cold weather. At higher temperatures, the longer setting time is desirable in most cases. As with other concrete exhibiting slower setting times, care may need to be taken to minimize the loss of moisture that causes plastic-shrinkage cracking.

6.3—Air entrainment

Air entrainment can be achieved in slag-cement concrete using the same production methods and air-entraining admixtures as portland-cement concrete. Generally, the amount of air-entraining admixture required to achieve a given air content is similar to that required in an equivalent

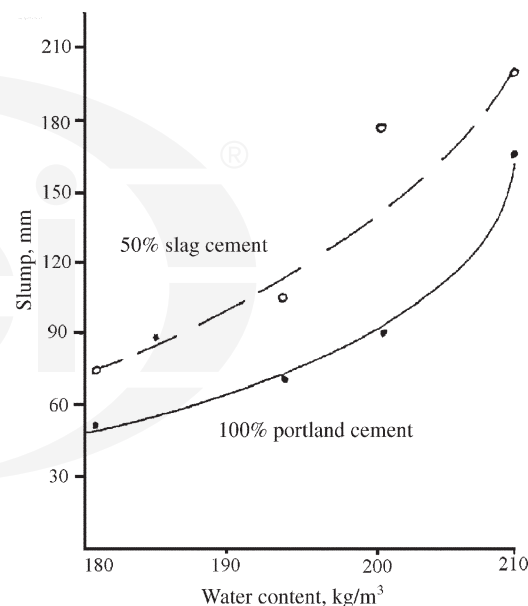


Fig. 6.1b—Effect of water content on slump of concrete mixtures with and without slag cement (Meusel and Rose 1983) (Note: 25.4 mm = 1 in.; 1 kg/m³ = 1.69 lb/yd³).

portland-cement concrete, with no more variability than expected with the portland cement mixture. The specified air-entraining admixture dose will need to be determined via testing, as is done for portland-cement concrete.

6.4—Bleeding

Bleeding capacity and bleeding rate of concrete are influenced by many factors, including the ratio of the surface area of solids to the unit volume of water, air content, subgrade conditions, and concrete thickness. When slag cements are used, bleeding characteristics can be estimated depending on the fineness of the slag cement compared with that of the portland cement and the combined effect of the two cementitious materials. When slag cement is finer than portland