Slag Cement in Concrete and Mortar

Reported by ACI Committee 233

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[†]ACI Committee 233 expresses its gratitude to the late Bryant Mather. From his pioneering work until his death, Bryant had a profound influence on the understanding, development, and promotion of the use of slag cement in concrete.
The committee acknowledges the contributions of Mark D. Luther, Past Chair, and Associate Member David Scott to the development of this report.

Previously, ACI and other standard- and code-writing organizations referred to slag cement as ground granulated blast-furnace slag (GGBFS). Throughout the industry, however, the term slag cement has been the more contemporary and commonly used terminology. ACI Committee 233, Ground Slag in Concrete, decided to review the terminology relating to this material. In 2001, the slag cement manufacturers, represented by the Slag Cement Association (SCA), approached the committee and requested a change in terminology from GGBFS to slag cement.

The technical merits of the terminology in question, as well as the effect on the industry, have been analyzed and debated. Finding the request from the SCA as appropriate and reasonable, the committee decided to make the change in terminology.

ACI Committee 233 and SCA have made similar requests to various ACI and ASTM technical and terminology committees to update or revise their definitions and descriptions of this and related materials.

Subsequently, in this document, with the exception of some referenced publications, the term ground granulated blast-furnace slag has been replaced with the term slag cement.

The use of iron blast-furnace slag as a constituent in concrete as an aggregate, a cementitious material, or both, is well known. Recent attention has been given to the use of slag cement as a separate cementitious constituent in concrete. 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; concrete; granulated blast-furnace slag; hydraulic cement; mixture proportion; mortar; portland cement; slag cement; specification.

CONTENTS

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CHAPTER 1—GENERAL INFORMATION
1.1—History

The use of ground granulated iron blast-furnace slag cement (slag cement) as a cementitious material dates back to 1774 when Loriot made a mortar using slag cement 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 iron blast-furnace slags were later investigated by Michaelis, Prussing, Tetmayer, Prost, Feret, and Green. Their investigations, 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).

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 m^3 (863,000 yd^3) 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) (Waterways Experiment Station 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, Ala. Each slag was activated with 1.5% sodium hydroxide and 1.5% 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% 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 by the committee 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. In 2000 there were at least nine companies supplying slag cement in the United States, up from just two in 1990. There are several companies making slag cement in Canada and Mexico, some of which was imported to North America in the late 1990s.

According to Solomon (1991), 13,293,000 Mg of iron blast-furnace slag was sold or used in the United States during that year. Today, much of this material could be used for the production of slag if granulating facilities were available at all furnace locations. More sources of slag cement may become available due to energy and environmental stimulus.

The majority of slag cement is batched as a separate ingredient at concrete production plants. A significant portion of the slag cement is used in making 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 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.

Slag from the production of metals other than iron differs greatly in composition and is not within the scope of this report.

1.3—Terminology
1.3.1 *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.

air-cooled blast-furnace slag—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.

expanded blast-furnace slag—the lightweight, cellular material obtained by controlled processing of molten blast-furnace slag with water or water and other agents, such as steam, compressed air, or both.

granulated blast-furnace slag (GBFS)—the glassy granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water.

ground granulated blast-furnace slag (GGBFS)—see cement, slag. In this report, the more commonly used "slag cement" has replaced ground granulated blast-furnace slag.

cement, blended—a hydraulic cement consisting essentially of an intimate and uniform blend of granulated blast-furnace slag and hydrated lime; or an intimate and uniform blend of portland cement and granulated blast-furnace slag, portland cement, and pozzolan, or portland blast-furnace slag cement and pozzolan, produced by intergrinding portland cement clinker with the other materials or by blending portland cement with the other materials, or a combination of intergrinding and blending.

cement, portland blast-furnace slag—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.

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

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

1.4—Environmental considerations
The use of slag cement in concrete and mortar is an environmentally sound and efficient use of existing resources. The use of slag cement has several benefits, including reduced energy, reduced greenhouse gas emissions, and reduced virgin raw materials. Recognizing the positive environmental impacts of using slag cement, the Environmental Protection Agency (EPA) actively encourages the expanded use of slag cement, indicated as follows.

Responding to Executive Order 12873 titled "Federal Acquisition, Recycling, and Waste Prevention," the EPA

Table 1.1—Range of chemical composition of blast-furnace slags in the United States and Canada

Chemical constituents (as oxides)[*]	Range of composition, % by mass
SiO_2	32 to 42
Al_2O_3	7 to 16
CaO	32 to 45
MgO	5 to 15
S	0.7 to 2.2
Fe_2O_3	0.1 to 1.5
MnO	0.2 to 1.0

[*]Except for sulfur.

issued a Comprehensive Procurement Guideline (U.S. Environmental Protection Agency 1994) that designated a number of items, including cement and concrete containing slag cement, as products made with recovered materials. Section 6002 of the Resource Conservation and Recovery Act (RCRA) requires agencies using appropriated federal funds to purchase products composed of the highest percentages of recovered materials practicable. The EPA (U.S. Environmental Protection Agency 1994) also issued a Recovered Materials Advisory Notice (RMAN) requiring that procuring agencies ensure that their guide specifications do not inappropriately or unfairly discriminate against the use of slag cement in blended cement and in concrete.

1.5—Origin of blast-furnace slag
In the production of iron, the blast furnace is continuously charged from the top with iron oxide (ore, pellets, sinter), fluxing stone (limestone or dolomite), and fuel (coke, typically). 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 about 1500 °C.

1.6—Chemical and physical properties
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. Typically, silica, calcium, aluminum, magnesium, and oxygen constitute 95% or more of the blast-furnace slag. Table 1.1 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 1.1 are much greater than those from an individual plant. Modern blast-furnace technology produces low variability in the compositions of both the iron and the slag from a single source.

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 4.75 mm (No. 4) sieve, composed predominantly of glass. This product is referred to as granulated blast-furnace slag. The potential activity of a granulated blast-furnace slag depends, to a large extent, on the chemistry and
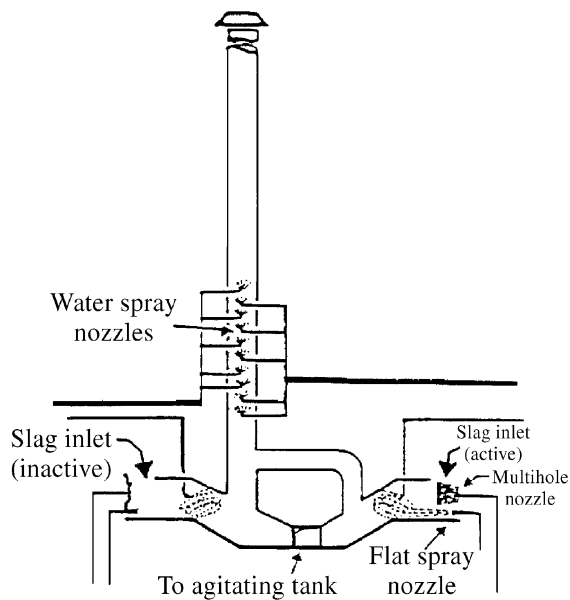
Fig. 1.1—Configuration of blast-furnace slag water granulator to include steam-condensing tower (Hogan and Meusel 1981).

Fig. 1.2—Blast-furnace slag pelletization process, using a minimum of water usually applied at the vibrating feed plate (Hogan and Meusel 1981).

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.

1.7—Processing

Quenching with water is the most common process for granulating 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 about 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 the boiling point of water, producing slag particles with a high glass content. This material is called granulated blast-furnace slag (GBFS). 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. 1.1.

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. 1.2). 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).
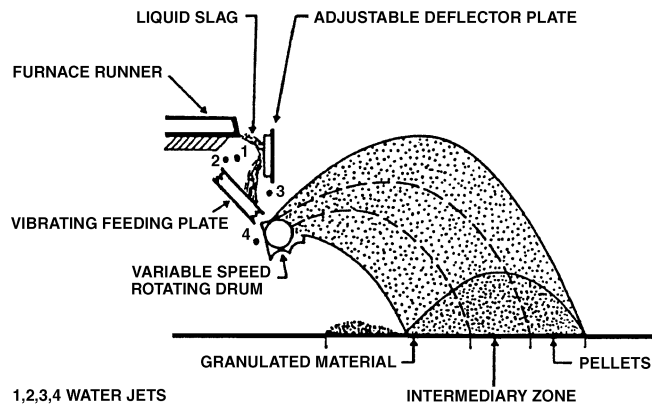
After the GBFS is formed, it must be dewatered, dried, and ground before it is used as a cementitious material. Magnets are often used before and after grinding to remove residual metallic iron. For increased cementitious activity at early ages, the slag is typically ground finer than portland cement. As with portland cement and pozzolans, the rate of reaction increases with the fineness.

1.8—Specifications

ASTM C 989, first adopted in 1982, provides for three strength grades of slag cements. The grade depends on the relative 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 C 989 specifies total alkali limits and 28-day compressive strengths for the reference cement.

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

SAI = slag-activity index, % = $(SP/P) \times 100$;
SP = average compressive strength of the 50:50 slag-reference portland cement mortar cubes, MPa (psi); and
P = average compressive strength of reference cement mortar cubes, MPa (psi).

Classification can be found in Table 1.2 (adapted from ASTM C 989).

In addition to requirements on strength performance, ASTM C 989 limits the residue on a 45 mm (No. 325) sieve to 20% and the air content to a maximum of 12%.

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

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 C 595 covers blended cements. Three types of such cements are addressed: 1) slag-modified portland cement [Type I (SM)], which contains less than 25% slag cement; 2) portland blast-furnace slag cement (Type IS), which contains 25 to 70% slag cement; and 3) slag cement (Type S), which contains

Table 1.2—Slag-activity index standards for various grades as prescribed in ASTM C 989

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

70% or more slag cement. These cements may be ground together or ground separately and blended.

ASTM C 1157 was issued in 1992 as the first performance specification for hydraulic cements, and it features six blended cement types. Blast-furnace slag may be used as a component in the production of ASTM C 1157 cement.

1.9—Hydraulic activity

There is general agreement among researchers (Smolczyk 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 (CSH). As seen in the phase diagram in Fig. 1.3, portland cement and slag cement lie in the same general field, although slag cement has a higher silica content.

When slag cement is mixed by itself with water, initial hydration is 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 CSH. Regourd (1980a,b,c) 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,c), 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. Initially and during the 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. 1.4).

With increasing temperature, the alkali hydroxides from the cement have greater solubility; therefore, they predominate in promoting the early reactions of the slag cement.
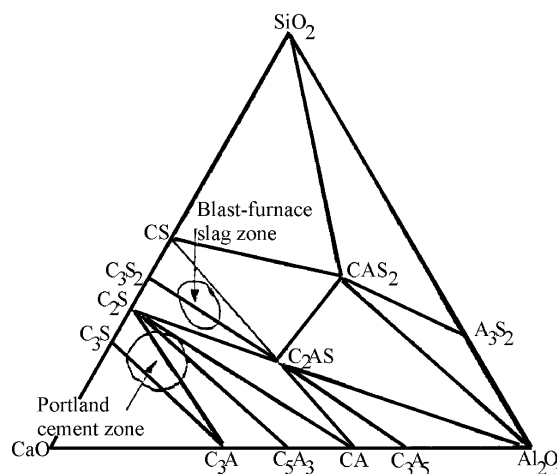

Fig. 1.3—Phase diagram indicating composition of portland cement and blast-furnace slag in the system CaO-SiO$_2$-Al$_2$O$_3$ (based on Lea [1971] and Bakker [1983]).
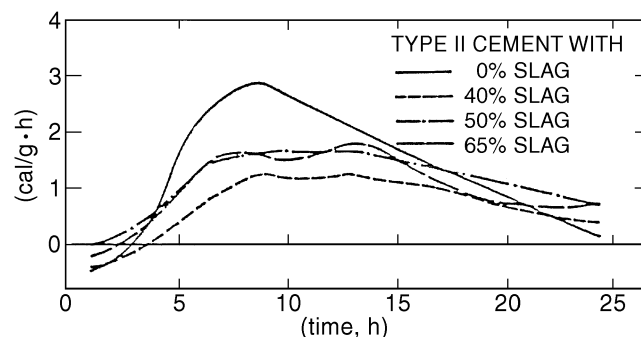

Fig. 1.4—Rate of heat liberation of cements with and without slag cement at 27 °C (80 °F) (Roy and Idorn 1982).

Forss (1982) and Voinovitch, Raverdy, and Dron (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.

1.10—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;

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; and

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 C 989 slag-activity index is often used as a basic criterion for evaluating the relative cementitious potential of a slag cement. Furthermore, proportioning for particular performance requirements should be based on tests of concrete including the same materials intended to be used in the work.

CHAPTER 2—STORAGE, HANDLING, AND BATCHING

2.1—Storage

As is the case with portland cement and most pozzolans, 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.

2.2—Handling

Slag cements are handled with the same kinds of equipment as portland cement. The most commonly used items 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.

2.3—Batching

Slag cement should be batched by mass in accordance with the requirements ASTM C 94 or CSA A 23.5. When slag cement is batched cumulatively in the same weigh hopper with portland cement, the slag cement should follow the batching of portland cement. 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 3—PROPORTIONING CONCRETE CONTAINING SLAG CEMENT

3.1—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 70% by mass of the total cementitious material. These proportions are in line with those established in ASTM for the production of Type IS portland blast-furnace slag cement.

There appears to be an optimum blend of slag cement and portland cement that produces the greatest strength at 28 days. This optimum amount of slag cement is usually 40 to 50% by mass of the total cementitious material, although this relationship varies depending on the grade of slag cement (Hogan and Meusel 1981; Fulton 1974).

Other considerations that determine the proportion of slag cement might include the requirements for permeability,

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% by mass of total cementitious material, unless previous testing with a particular slag cement has indicated that a lower percentage is adequate (Chojnacki 1981; Hogan and Meusel 1981; Fulton 1974; Lea 1971; Hooton and Emery 1990).

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, or accelerated curing is provided.

Proportioning concrete mixtures using slag cement and portland cement added separately to the mixer typically has two advantages over the use of blended cements:

1) Each material can be ground to its own optimum fineness; and

2) The proportions can be optimized to suit the particular project requirements.

The first significant use of separately ground slag cement was in South Africa where the proportion of slag was 50% of the cementitious materials due to batching convenience and durability considerations (Wood 1981).

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. Due to the high proportions of slag cement commonly used, however, allowances should be made for changes in solid volume due to the difference in relative density (specific gravity) of slags (2.85 to 2.94 Mg/m^3) and portland cement (3.15 Mg/m^3).

While the differences in absolute volume of the cementitious paste is minimal with regard to the yield of concrete, it can change 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 will improve 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.

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 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 material ratio (*w/cm*).

As discussed in Section 4.1, water demand for given slump may generally be 3 to 5% lower in concrete containing

slag cement than that found with concrete without slag cements (Meusel and Rose 1983). Exceptions may be found, and these should be identified in the trial mixture proportioning studies.

3.2—Ternary systems

The use of slag cement in combination with portland cement and pozzolans, such as fly ash and silica fume, is not uncommon. The use of a ternary system may have some economic benefits, but it is generally used for improving engineering properties, such as high-performance concrete.

Combinations of slag cement, portland cement, and silica fume were used in concrete mixtures in high-strength applications for the Scotia Plaza in Toronto (Bickley et al. 1991) and Society Tower (*Engineering News Record* 1991) in Cleveland, Ohio. Combinations of slag cement, fly ash, and portland cement have been used as ballast for tunnel sections when low heat generation in mass concrete was desired. 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).

Since 1994, the Ohio Department of Transportation has used high-performance concrete containing portland cement with 30% slag cement, 4.5% silica fume, and a 0.38 *w/cm* (Ohio Department of Transportation 1994) for the construction of bridge decks. The Federal Aviation Administration allows the use of slag cement with fly ash (Federal Aviation Administration 1999). Beginning in 1997, mainline pavements have featured combinations of portland cement with slag cement and fly ash in Iowa, Minnesota, and Wisconsin.

There have been combinations of portland cement with slag cement and fly ash that have been used in the United States in general-use concrete. Use of combinations of these materials appears to be increasing.

Among the effects resulting from adding silica fume to ternary systems are increased strength and reduced permeability at early ages. In addition, slag cement has been used in combination with portland cement and ground quartz (silica flour) in autoclaved concrete masonry (Hooton and Emery 1980).

3.3—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 changes in the dosage rate of air-entraining admixtures are sometimes necessary if the fineness or air content of the slag cement is different than that of the portland cement. The amount of high-range water-reducing admixtures (HRWRAs) required to produce flowing concrete is usually 25% less than that used in concrete not containing slag cement (Wu and Roy 1982). When the dosage rate is 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.

CHAPTER 4—EFFECTS ON PROPERTIES OF FRESH CONCRETE

4.1—Workability

Fulton (1974) investigated workability 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 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. 4.1). Considering his earlier findings, Fulton 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 were compared. In all cases, the consolidation of the concrete containing 50% 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. 4.2).

Osborne (1989) presented results of slump, Vebe, and compacting factor tests for concrete containing 0, 40, and 70% slag cement. The tests showed that as the percentage of slag cement increased, the *w/cm* had to be reduced to maintain workability properties more or less similar to the concrete with no slag cement. Wimpenny, Ellis, and Higgins (1989) found that in concrete with constant *w/cm*, the slump increased significantly with increasing slag cement replacement.

4.2—Time of setting

Using the ASTM C 403 penetration resistance test, Luther and Mikols (1993) showed that the time of setting of concrete made with 40% slag cement was not affected by slag cement fineness over the range of 400 to 1400 m^2/kg range (Blaine fineness). Luther et al. (1994) presented information indicating that at approximately 21 °C (70 °F), the setting time was increased by 1 h at 35 to 40% 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% slag cement is used as a replacement for portland cement in concrete mixtures. The degree to which the setting
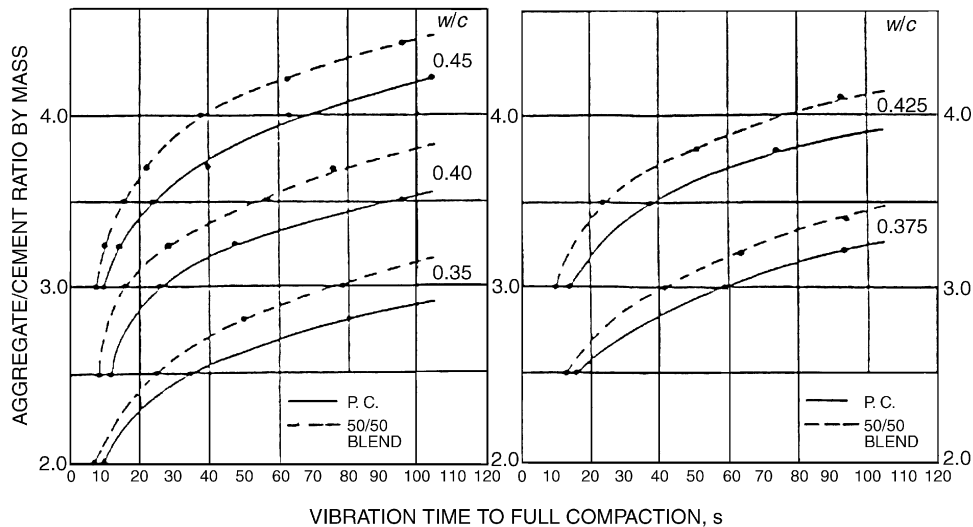
Fig. 4.1—Relationship between response to vibration of concrete mixtures made with portland cement with mixtures containing 50% slag cement (Fulton 1974).
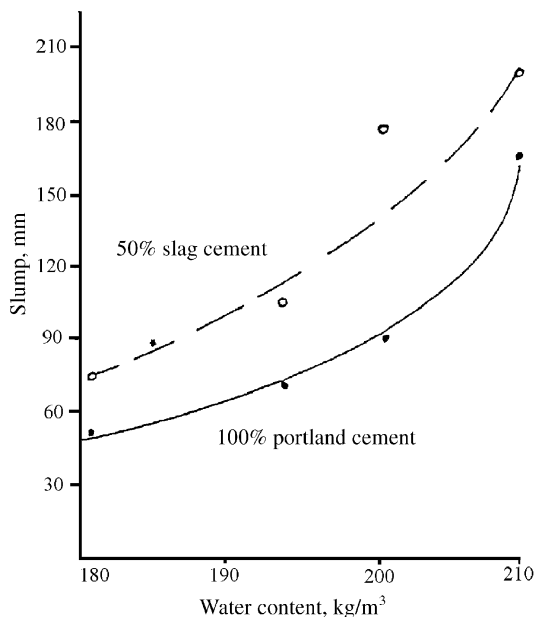

Fig. 4.2—Effect of water content on slump of concrete mixtures with and without slag cement (Meusel and Rose 1983) (Note: 25.4 mm = 1 in.; 1 kg/m³ = 1.69 lb/yd³).

time is affected depends on the temperature of the concrete, the amount of slag cement used, the *w/cm*, and the characteristics of the portland cement (Fulton 1974). The amount of portland cement is also important. Hogan and Meusel (1981) found that for 50% slag cement, the initial setting time is increased 1/2 to 1 h at 23 °C (73 °F); little if any change was found above 29 °C (85 °F).

Although significant retardation has been observed at low temperatures, addition of conventional accelerators, such as calcium chloride or non-chloride 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.

4.3—Bleeding

Bleeding capacity and bleeding rate of concrete are influenced by a number of 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 cement and is substituted on an equal-mass basis, bleeding may be reduced; conversely, when the slag cement is coarser, the rate and amount of bleeding may increase.

4.4—Rate of slump loss

Meusel and Rose (1983) indicated that concrete containing slag cement at 50% substitution yielded slump loss equal to that of concrete without slag cement. Experiences in the United Kingdom indicated reduced slump loss, particularly when the portland cement used in the blend exhibited rapid slump loss, such as that caused by false-set characteristics of the cement (Lea 1971).

CHAPTER 5—EFFECTS ON PROPERTIES OF HARDENED CONCRETE AND MORTAR
5.1—Strength

Compressive and flexural strength gain characteristics of concrete containing slag cement can vary over a wide range. Compared with portland cement concrete, the use of Grade 120 slag cements typically results in reduced strength at early ages (one to three days) and increased strength at later ages (seven days and beyond) (Hogan and Meusel 1981). Use of Grade 100 results in lower strengths at early ages (1 to 21 days) but equal or greater strength at later ages. Grade 80 typically gives reduced strength at early ages, although, by the 28th

day, the strength may be equivalent to or slightly higher than a 100% portland cement mixture.

The extent to which slag cement affects strength depends on the slag activity index of the particular slag cement and the fraction in which it is used in the mixture. Figure 5.1 indicates that the mortar strength development of 50% blends depends upon the grade of slag cement as defined in ASTM C 989. Consistent and stable long-term strength gain beyond 20 years has been documented for concrete made with portland blast-furnace slag cement (Type IS) while exposed to moist or air curing (Wood 1992).

Other factors that can affect the performance of slag cement in concrete are *w/cm*, physical and chemical characteristics of the portland cement, and curing conditions. As seen in Fig. 5.2, the percentage of strength gain, relative to portland-cement concrete, with Grade 120 slag cement is greater in mixtures with a high *w/cm* than in mixtures with a low *w/cm* (Fulton 1974; Meusel and Rose 1983). Malhotra (1980) also noted the same trend.

The temperature at which concrete is cured will have a great effect on strength, particularly at early ages. Concrete containing slag cement responds well to elevated temperature curing conditions (Roy and Idorn 1982). In fact, strength exceeding that of portland-cement concrete at 1 day and beyond has been reported for accelerated curing conditions (Hogan and Meusel 1981; Fulton 1974; Lea 1971). Conversely, lower early-age strength is expected for concrete containing slag cement when cured at normal or low temperatures.

The proportion of the slag cement used affects the strength and rate of strength gain as noted in Fig. 5.3. When highly active slag cements have been used, the greatest 28-day strengths are found with blends as high as 65% slag cement (Fulton 1974; Hogan and Meusel 1981; Meusel and Rose 1983). Where early-age strengths are concerned, the rate of strength gain is generally inversely proportional to the fraction of slag cement used in the blend. Figure 5.4 compares compressive strength development of various blends of slag cement and portland cement with a portland-cement mixture only.

5.2—Modulus of rupture

Of particular interest is the effect of slag cement when concrete is tested for flexural strength (modulus of rupture). When comparisons are made between concrete with and without slag cement, where the slag cement is used at proportions designed for greatest strength, the blends generally yield higher modulus of rupture at ages beyond 7 days (Fulton 1974; Malhotra 1980; Hogan and Meusel 1981) (Fig. 5.5). This is believed to be a result of the increased density of the paste and improved bond at the aggregate-paste interface.

Early studies on flexural strength were conducted with Type IS blended cements. Klieger and Isberner (1967) found essentially the same flexural strength in concrete containing portland blast-furnace slag cement as compared with Type I portland-cement concrete. Stutterheim, as quoted by Fulton (1974), also confirmed this using concrete containing equal amounts of slag cement and portland cement and concrete with portland cement only.
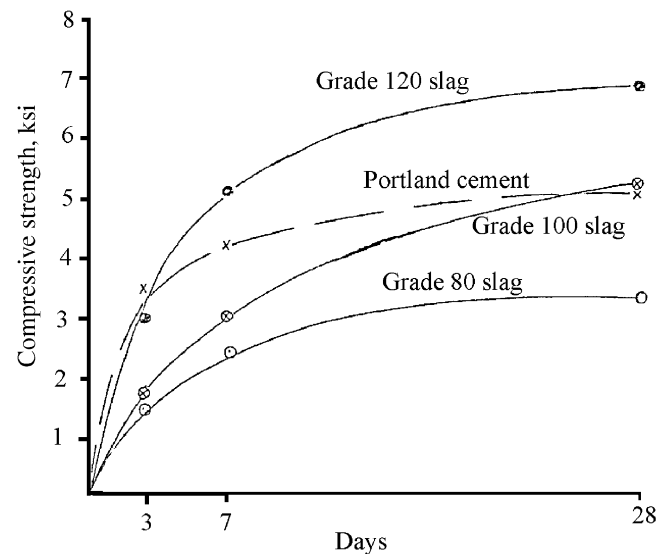
Fig. 5.1—Strength relationship of mortar containing typical slag cements meeting ASTM C 989 requirements, compared with portland cement mortar (data originate from Task Group E-38.06.02 report). (Note: 1 ksi = 6.89 MPa.)

Fig. 5.2—Effect of w/cm ratio on compressive strength of mixtures containing 50% slag cement, expressed as a percentage of mixtures made with only portland cement (Meusel and Rose 1983).

Fig. 5.3—Influence of slag cement on mortar cube compressive strength (Hogan and Meusel 1981). (Note: 1 ksi = 6.89 MPa.)

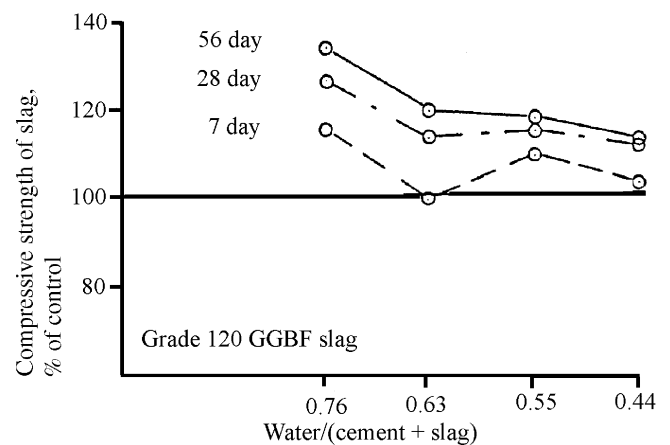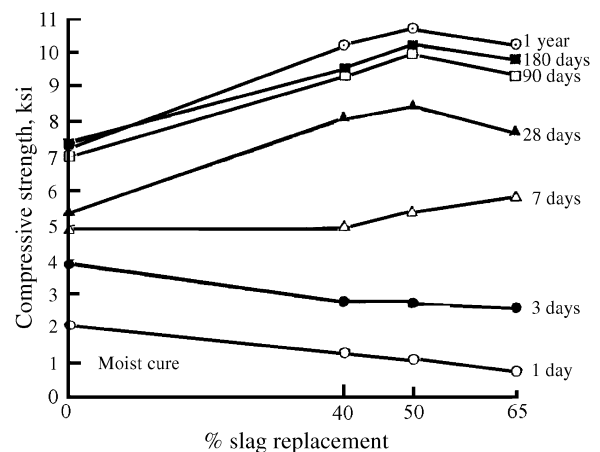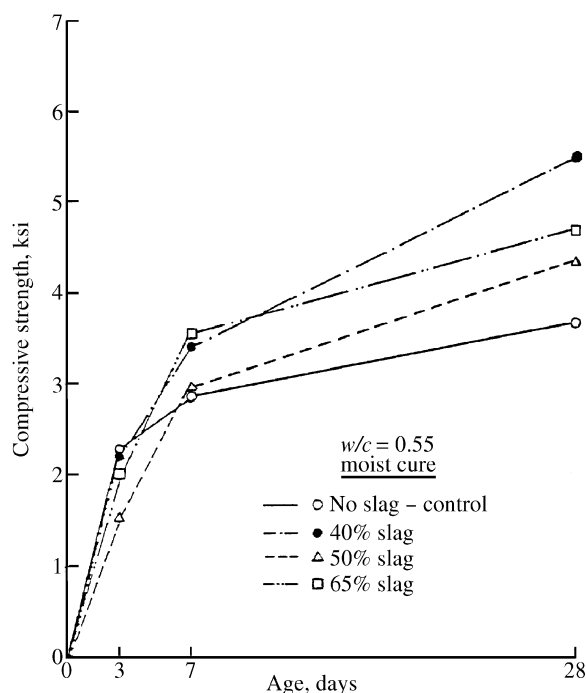*Fig. 5.4—Compressive strength of concrete containing various blends of slag cement compared with concrete using only portland cement as a cementitious material (Hogan and Meusel 1981). (Note: 1 ksi = 6.89 MPa.)*
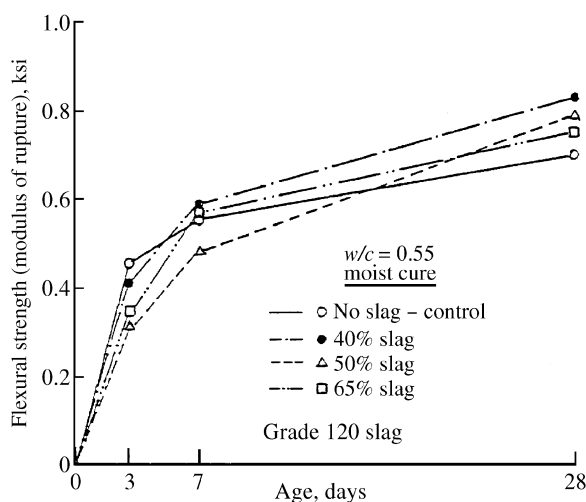

Fig. 5.5—Flexural strength (modulus of rupture) of concrete containing various blends of slag cement, compared with concrete using only portland cement as cementitious material (Hogan and Meusel 1981). (Note: 1 ksi = 6.89 MPa.)

5.3—Modulus of elasticity

Research conducted with four different slag cement sources by Brooks, Wainwright, and Boukendakji (1992) concluded that the influence of the slag cement source on strength, modulus of elasticity, and long-term deformation was small and could not be associated quantitatively with chemical composition. They further concluded that when tested under different moisture conditions, the secant modulus varied. The secant modulus of elasticity of water-stored concrete containing slag cement was similar at early

ages and greater at later ages when compared with concrete containing portland cement only. Conversely, the opposite trend occurred for mature concrete stored in air.

5.4—Creep and shrinkage

Published data on creep and shrinkage of concrete containing slag cement indicate somewhat conflicting results when compared with concrete containing only portland cement. These differences are likely to be affected by differences in maturity and characteristics of the portland cement from which the concrete specimens were made. Overall, the published information suggests that drying shrinkage is similar in portland-cement concrete and concrete containing slag cement.

Klieger and Isberner (1967) found few differences between concrete containing slag cement and concrete containing only portland cement. On the other hand, Fulton (1974) reported generally greater creep and shrinkage when various slag cement blends were compared with portland cement. Cook, Hinczak, and Duggan (1986) tested concrete made with 35% slag cement and two different portland cements. Minimum shrinkage or creep were reported to have different optimum gypsum contents. Whether the blended cement was made by interblending or intergrinding also affected the optimum gypsum content.

Brooks, Wainwright, and Boukendakji (1992) investigated the time-dependent properties of four different slag sources and varying slag cement replacement levels between 30 and 70% by mass of total cementitious material. They concluded that, compared with concrete containing only portland cement, concrete containing slag cement had similar or greater long-term strength, similar shrinkage, lower basic creep, and similar or lower total creep.

Research commissioned by the Ohio Department of Transportation on high-performance concrete mixtures for application in bridge decks indicated that concrete containing 30% slag cement showed less drying shrinkage than the 100% portland-cement mixture (Lankard 1992). The combination of 30% slag cement with silica fume showed still less drying shrinkage.

Sivasundaram and Malhotra (1991) found that slag cement concrete with varying cementitious material contents and slag cement replacement amounts showed shrinkage to be similar at lower replacement percentages and less at higher replacement percentages than the 100% portland-cement mixtures. Evaluating roller-compacted concrete, Togawa and Nakamoto (1989) found that the use of slag cement reduced shrinkage.

Tazawa, Yonekura, and Tanaka (1989) concluded that the drying shrinkage and creep of slag cement concrete was less than that of 100% portland-cement concrete when standard 28-day curing was used. The total cementitious material contents in this concrete ranged from 270 to 370 kg/m^3 (455 to 624 lb/yd^3), and the slag cement ranged in Blaine fineness from 441 m^2/kg to 585 m^2/kg. The report mentioned that for specimens without adequate curing, the shrinkage was higher than the reference portland cement mixtures, and the specific creep was lower.

A potential for reducing shrinkage potential in a concrete mixture may be realized when the higher strength afforded by slag cement in a mixture allows the use of a lower total cementitious materials (paste) content. Such adjustment should only be done when the specification allows it and it is otherwise appropriate.

5.5—Influence of curing on performance

Regardless of the cement or the blends of cementitious material used, concrete should be maintained at proper moisture and temperature condition during its early stages to fully develop its strength and durability potential. There has been considerable discussion regarding the effects of curing on concrete containing portland blast-furnace slag cement and concrete containing slag cement as a separate constituent. In Mather's 1957 study comparing Type II cement concrete with portland blast-furnace slag cement concrete, he found that both types of concrete resulted in strength loss to the same degree when curing was stopped at three days. Conversely, Fulton (1974) reports that concrete containing more than 30% slag cement is more susceptible to strength loss due to poor curing conditions than concrete without slag cement. He attributes this susceptibility to reduced formation of hydrate at early ages leading to increased loss of moisture that would otherwise be available for hydration to continue. There is no doubt that, as with all cementitious materials, the rate and degree of hydration is reduced by the loss of moisture at an early age, with a resulting decrease in ultimate strength gain. To attain proper strength and durability, curing should follow the procedures prescribed in ACI 308.

5.6—Color

Slag cement is considerably lighter in color than most portland cement and will produce a lighter color in concrete after curing. In certain operations, up to 30% slag cement has been used to replace white portland cement without a noticeable color difference in the cured product.

There is a unique characteristic of concrete containing slag cement, either added separately or in blended cements, in that during the second to fourth days after casting, a blue, green, or blue-green coloration may appear. Coloration diminishes with age as oxidation takes place. This coloration is attributed to a complex reaction of the sulfides in the slag cement with other compounds or elements in the cement. The degree and extent of the coloration depends on the chemistry of the slag, the rate of oxidation, the percentage of slag cement used, the curing conditions, and the degree of surface densification during finishing (denser being more colored and darker), among other factors. Where color is important, correctly timed exposure to air, sunlight, or wetting and drying promotes oxidation of the concrete surface. Concrete containing slag cement has been found to yield blue coloration for extended periods when continuously exposed to water, such as in swimming pools or when sealers are applied at early ages. The interior of the concrete may retain a deep blue, green, or blue-green coloration for a considerable time period as might be observed on a freshly fractured concrete surface. When these faces are exposed to the atmosphere, however, the exposed area will oxidize to a uniform color.

Colored concrete can be achieved with concrete containing slag cement. Often the lighter shade of the cured and dried slag cement concrete presents some advantage for achieving colored concrete, for concrete block, and concrete pavers and other applications.

5.7—Effects on temperature rise in mass concrete

Slag cement, when used at appropriate replacement levels, can be an effective means of controlling temperature rise in mass concrete. In all cases, the incorporation of slag cement reduced the early rate of heat generation. This reduction is directly proportional to the proportion of slag cement used. The reduction in peak temperature and rate of heat gain is seen in Fig. 5.6, where in-place measurements were reported by Bamforth (1980) comparing concrete with 100% portland cement to concrete with 30% fly ash and concrete with 75% slag cement. The heat of hydration depends on the portland cement used and the activity of the slag cement. These mixtures with and without slag cement were tested using the heat of solution test method, ASTM C 186. The mixtures with slag cement produced the greater cumulative heat (Bamforth 1980; Hogan and Museul 1981; Roy and Idorn 1982). Although the heat of solution test method indicates total heat release potential of the cement, it does not indicate the rate of heat rise that is also important in mass concrete.

5.8—Permeability

The use of slag cement in hydraulic structures is well documented. The permeability of mature concrete containing slag cement is much lower than that of concrete not containing slag cement (Hooton and Emery 1990; Roy 1989; Rose 1987). As the slag cement content is increased, permeability of the concrete decreases. The microstructure of the cementitious matrix is changed through the reaction of slag cement with the calcium hydroxide and alkalis released during the portland-cement hydration (Bakker 1980; Roy and Idorn 1982). Pores in concrete that normally contain calcium hydroxide are, in part, filled with calcium silicate hydrates resulting from the hydration of the slag cement (Bakker 1980; Mehta 1980; Roy and Idorn 1982). As pointed out by Mehta (1980), "the permeability of concrete depends on its porosity and pore-size distribution." The reduction in pore size due to slag cement is seen in Fig. 5.7, which compares the pore-size distribution in paste with and without slag cement. Where slag cements are used, reduction in the pore size occurred before 28 days after mixing (Bakker 1980; Mehta 1980; Roy and Idorn 1982). Another example of reduced penetrability is shown in Fig. 5.8 taken from Smolczyk (1977), where concrete of varying *w/cm* and slag cement content were evaluated for chloride diffusion over a period of two years.

5.9—Resistance to sulfate attack

Partial replacement of portland cement with slag cement improves the sulfate resistance of concrete. High resistance to sulfate attack has been demonstrated when the slag
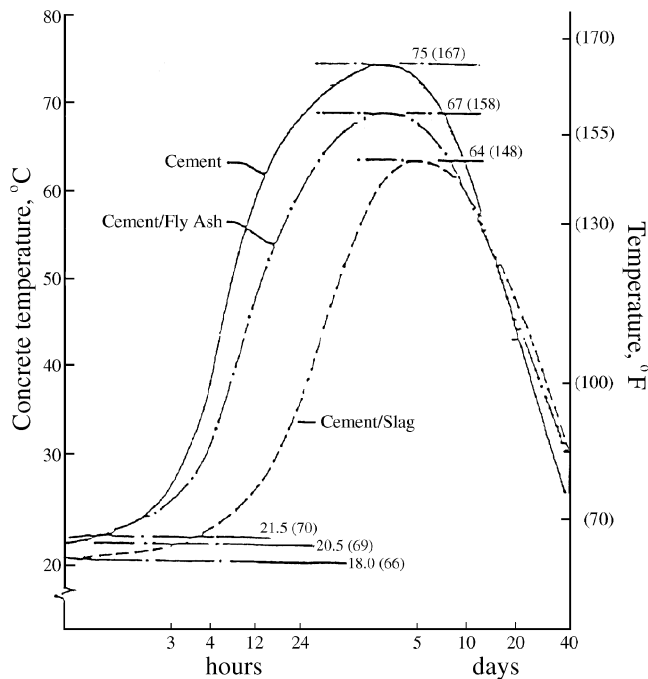
Fig. 5.6—Comparison of heat generated in mass concrete with portland cement, portland-cement fly ash, and portland-cement slag concrete mixtures (Bamforth 1980).
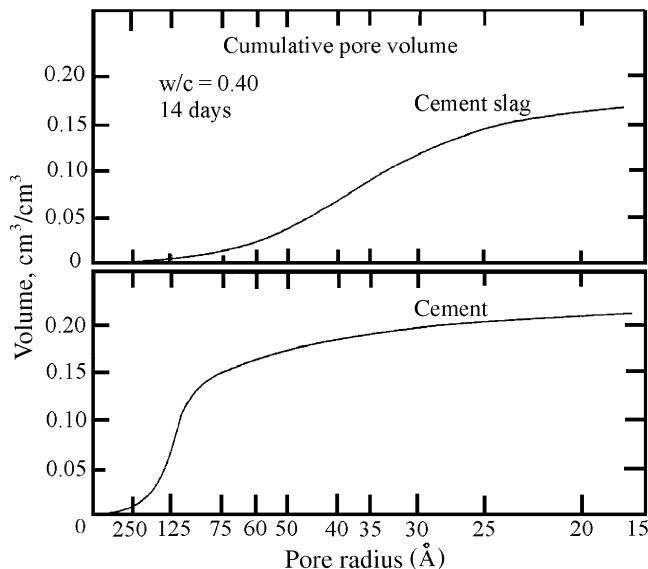

Fig. 5.7—Comparison of pore-size distribution of paste containing portland cement and paste containing 40% slag and 60% portland cement, tested by mercury intrusion (Roy and Parker 1983).

cement proportion exceeds 50% of the total cementitious material where Type II cements were used (Hogan and Meusel 1981). Additional testing of slag cement in Canada (Chojnacki 1981) showed that 50% blends of slag cement with Type I portland cement containing up to 12% C_3A have sulfate resistance equivalent to that of Type V cements. The slag cement was reported to have 7% Al_2O_3 (Chojnacki 1981). As reported by Hooton and Emery (1990), a minimum
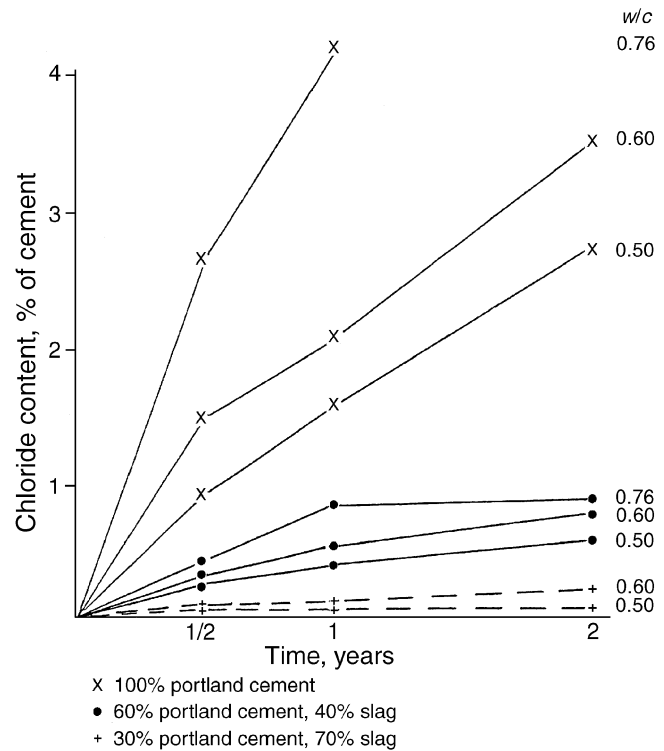

Fig. 5.8—Results of chloride content in 20.3 to 40.6 mm (0.8 to 1.6 in.) deep layers in concrete beams stored in 3.0 molar solution of NaCl (Smolczyk 1977).

amount of slag cement is required to provide high sulfate-resisting properties to concrete. Their results, using ASTM C 1012, indicate that this minimum would be 50% or greater when used with Type I portland cement having a C_3A content up to 12%, as long as the Al_2O_3 content of the slag cement was lower than 11% (Fig. 5.9).

Where slag cement is used in sufficient quantities, several changes occur that improve resistance to sulfate attack. Those changes include:

1) The C_3A content of the mixture is proportionally reduced depending on the percentage of slag cement used. Lea (1971), however, reports that increased sulfate resistance depends not only on the C_3A content of portland cement but also the alumina content of the slag cement. Lea further reports from tests made by Locher that where the alumina content of the slag cement is less than 11%, increased sulfate resistance was found, regardless of the C_3A content of the portland cement where blends between 20 and 50% slag cement were used;

2) Through the reduction of soluble calcium hydroxide by the hydration of slag cement, the environment for the formation of calcium sulfoaluminate, the primary cause of deterioration due to sulfate attack, is reduced; and

3) Investigations indicate that resistance to sulfate attack depends greatly on the permeability of the concrete or cement paste (Bakker 1983; Mehta 1980; Roy and Idorn 1982). Again, the formation of calcium silicate hydrates in pore spaces, normally occupied by alkalies and calcium

hydroxide, reduces the permeability of the paste and prevents the intrusion of the aggressive sulfates.

Hogan and Meusel (1981) demonstrated that slag was effective in reducing the expansion due to sulfate attack of mortar bars with either Type II or Type V cement; the results for the mortar made with Type II cement are illustrated in Fig. 5.10.

5.10—Reduction of expansion due to alkali-silica reaction (ASR)

Use of slag cement as a partial replacement for portland cement is known to reduce the potential expansion of concrete due to ASR (Bakker 1980; Hogan and Meusel 1981). The effectiveness of slag cement in controlling damaging expansion due to ASR was first reported in 1950 (Cox, Coleman, and White 1950). Since that time there have been more than 100 publications dealing with the affect of slag cement on ASR. In a review of the published literature, Thomas (1996) demonstrated that the efficiency of slag cement depends on the nature of the slag cement, the reactivity of the aggregate, and the alkali content of the portland cement. In most cases, 50% slag cement was sufficient for controlling damaging expansion in concrete with highly reactive aggregates and high-alkali cement.

Field studies in South Africa (Oberholster and Davies 1987; Oberholster 1989) have shown that 50% slag cement (by volume) eliminated damaging expansion seen in portland-cement concrete in beams and cubes, even when the alkali content of the concrete was augmented to compensate for the dilution of the portland cement.

In France and the Netherlands, ASR has been implicated in a few structures containing 35 to 40% slag cement (Cornielle 1988, Heijnen, Larbi, and Siemes 1996); however, there were no reported cases of ASR in concrete containing 50% or more slag cement. The apparent low incidence of ASR in the Netherlands has been attributed to the use of slag cements at such levels (Heijnen 1992; Heijnen, Larbi, and Siemes 1996).

Studies by Thomas and Innis (1998) examined the effect of slag cement on the expansion of concrete containing five reactive aggregates from Canada using a test similar to the ASTM C 1293 concrete prism test. Figure 5.11 shows the expansion of concrete prisms after two years of storage over water (that is, approximately 100% relative humidity) at 38 °C (100.4 °F). Between 35 and 50% slag cement was required to control the expansion of concrete containing alkali-silica reactive aggregate to less than 0.04% at two years. Slag cement was not effective, however, in controlling the expansion of the aggregate. The same paper reports that low-alkali cement (0.50% Na_2O equivalent) was also ineffective in controlling the expansion of concrete containing this aggregate. The combination of slag cement with relatively small amounts of silica fume conferred an additional measure of control to expansion caused by ASR.

The Appendix of ASTM C 989 reports that where slag cements are used in quantities greater than 40% of the total cementitious material, reduced expansion due to the ASR is found with cement having alkali contents up to 1.0%. Hogan and Meusel (1981) report (Fig. 5.12) that where slag cement
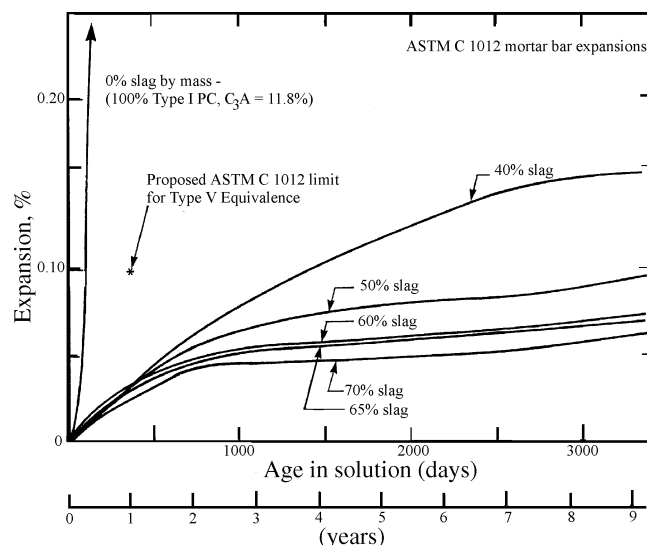

Fig. 5.9—Effect of various slag replacement levels on expansions in 50,000 mg/L SO_4 as Na_2SO_4 (slag Al_2O_3 = 8.4%).
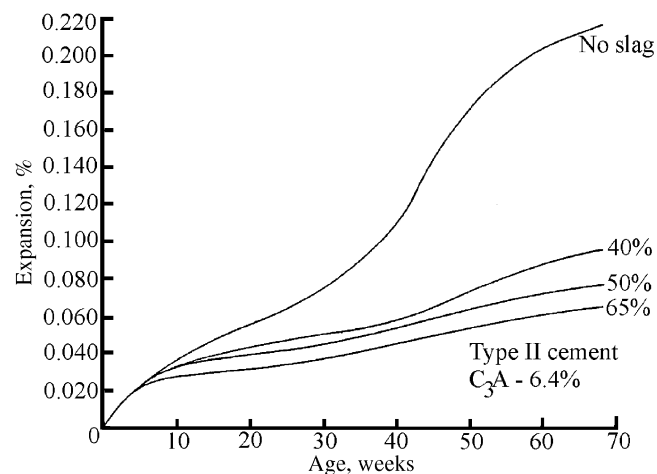

Fig. 5.10—Sulfate resistance of mortar bars, Wolochow test, Type II (Hogan and Meusel 1981).

contents are used in percentages from 40 to 65% of total cementitious material, expansion is virtually eliminated when tested in accordance with ASTM C 227. Their test used highly reactive Pyrex glass to obtain maximum expansion. Similar results were reported by Klieger and Isberner (1967) from tests in which portland and slag cements were used.

Results of tests using slag cement as a partial replacement for high-alkali cement with aggregate known to exhibit alkali-silica and alkali-carbonate reactions were reported by Soles, Malhotra, and Chen (1989). After two years of observation, the slag cement blends were found to be effective in reducing expansion, but the reduction was less than that found with the low-alkali cement. When used in combination with high-alkali cement, blends of 50% slag cement appear to be effective in reducing the potential of ASRs.

By the mid-1990s, the Mid-Atlantic states had collectively tested over 700 different aggregates for their potential to cause deleterious ASR expansion using the ASTM C 1260 mortar-bar test. After evaluating several slag cements from the eastern
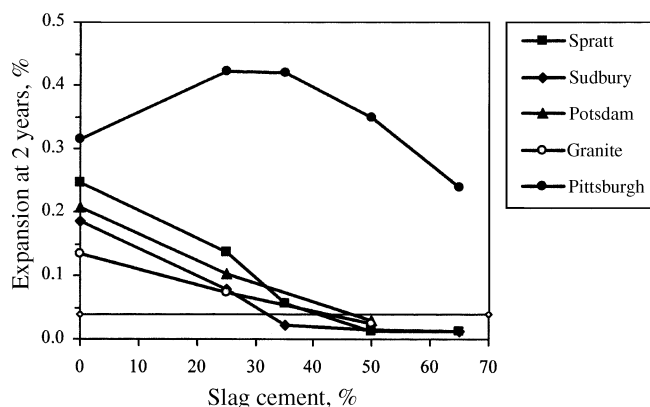
Fig. 5.11—Expansion of concrete prisms with various aggregates (Thomas and Innis 1998).
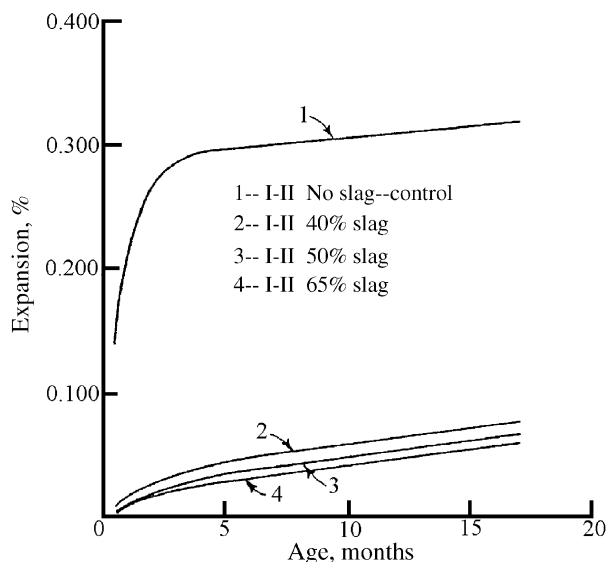

Fig. 5.12—ASTM C 228 potential alkali-aggregate reactivity for various slag replacements (Hogan and Meusel 1981).

seaboard, these states tended to require at least a 40% slag cement in concrete containing a potentially reactive aggregate where slag cement was the method of mitigation.

Resistance to ASR is attributed to the following influences on the cement paste:

1) Reduced permeability;

2) Change of the alkali-silica ratio;

3) Dissolution and consumption of the alkali species;

4) Direct reduction of available alkali in the system; and

5) Reduction of calcium hydroxide needed to support the reaction.

5.11—Resistance to freezing and thawing

Many studies related to resistance to freezing and thawing have been made using concrete containing slag cement. Results of these studies generally indicate that when concrete made with portland blast-furnace slag cement was tested in comparison with Type I and Type II cements, their resistances to freezing and thawing in water were essentially the same (Fulton 1974; Klieger and Isberner 1967; Mather 1957). As with all hydraulic cement concrete, proper air content and air-void system are necessary for adequate protection in freezing-and-thawing environments.

Air-entrained concrete containing 50% slag cement was found to be resistant to freezing and thawing, even though a measurable difference in mass loss was found when compared to the concrete made with Type II portland cement and tested using ASTM C 666 (Procedure A) (Hogan and Meusel 1981). Similar results were found by Malhotra (1980) using various percentages of slag cement with portland cement.

5.12—Resistance to deicing chemicals

Although some laboratory tests with Type IS cement indicate less resistance to deicing salts, many researchers have found, in field exposure, little difference when compared with concrete not containing slag cement (Klieger and Isberner 1967). Similar results were reported using blends of 50% slag cement and 50% portland cement (Hogan and Meusel 1981), or slag cement percentages in excess of 35% (Afrani and Rogers 1994).

Research conducted with slabs cast on grade and using ASTM C 672 tests, all using exterior residential concrete mixtures containing approximately 306 kg/m^3 (516 lb/yd^3) of cementitious material and with Grade 100 and Grade 120 slag cements, identified 25% slag cement to be an optimum amount for scaling resistance. Concrete with 25% slag cement was more resistant to scaling than portland-cement concrete. The laboratory portion of this work indicated that scaling resistance was consistently comparable to that of portland-cement concrete up to about 50% slag cement content (Luther et al. 1994). ACI 301 and ACI 318 allow up to 50% slag cement in severe-exposure-condition environments applicable to scaling resistance. Most research indicates that scaling is usually found when the concrete has combinations of a high *w/cm*, high percentages of slag cement, and low air content. As with all air-entrained concrete, it is prudent to measure the air content of freshly placed concrete to ensure that the required air content is being achieved.

5.13—Resistance to the corrosion of reinforcement

Many investigations have shown that reduced permeability of concrete containing slag cement significantly reduces the penetration of chloride ions within the concrete (Bakker 1980; Bakker 1983; Fulton 1974; Mehta 1980; Roy 1989; Rose 1987; Mehta 1980; Hogan and Meusel 1981). The reduction in permeability and the resistance to chloride-ion intrusion increases as the level of slag cement increases in the concrete mixture or mortar.

During the early use of concrete containing portland and slag cement, there was considerable concern regarding the potential harmful effects of sulfide sulfur in slag cement. Since then, many investigations have shown that the use of slag cements has no negative effect on the corrosion of steel (Fulton 1974; Lea 1971; Hogan and Meusel 1981). A slight reduction in the pH of pore solution does not have a negative impact on the passivity of reinforcing steel. The use of slag cement in good-quality concrete reduces concrete permeability, thus reducing the penetration of chloride ions and the depth of carbonation that promote corrosion of steel.

CHAPTER 6—USES OF SLAG CEMENT IN CONCRETE AND MORTAR

6.1—Introduction

Generally, slag cement blended with portland cement or as a separately added constituent may be used in most concrete and mortar applications and processes. The flexibility of using different proportions of slag cement provides the desired qualities of concrete that are most important to the owner, specifier, and concrete producer.

6.2—Ready-mixed concrete

Most producers of ready-mixed concrete that use slag cement do so in proportions of 50% of total cementitious material during warm weather (Wood 1981). This proportion usually produces the greatest strength and most favorable cost-to-benefit ratio. Proportions of slag cement as low as 20 to 30% have been used during periods of colder weather when setting time and rate of strength gain might be slower. In those jobs requiring performance characteristics, such as sulfate resistance or reduced heat of hydration, concrete mixtures containing more than 50% slag cement might be more appropriate. On the other hand, when early strengths are required to facilitate quick form removal or when thin sections are placed at low temperatures, blends containing less than 50% are recommended.

Particular advantages in the use of slag cement as a separate cementitious material in ready-mixed concrete are:

a) Increased flexibility to meet individual job requirements;

b) Reduced cost of cementitious material;

c) Improved workability;

d) Reduced slump loss and associated strength reduction in hot-weather concrete applications; and

e) Increased compressive and flexural strength with slag cement Grade 100 or 120.

6.3—Concrete products

The use of slag cement in precast concrete products is usually restricted by the requirements for early strength (1 day) and the curing cycle used. Under normal curing conditions, 1-day strength is usually lower in concrete containing slag cement, particularly when high percentages of slag cement are substituted for the portland cement. Therefore, proportions with less slag cement, accelerating admixtures, or both are required to achieve the desired stripping and handling strength.

Where accelerated curing conditions are used, slag cement blends of 40 to 60% of total cementitious material are applicable in most concrete mixtures and curing cycles. Slag cements respond favorably to accelerated curing, and increased strength at 1 day may be obtained when Grade 120 slag cements are used with curing temperatures exceeding 54.4 °C (130 °F) (Hogan and Meusel 1981). Improved early strength of slag cement to accelerated curing is an important attribute in the manufacture of precast and prestressed components for marine exposure where high durability is needed.

Slag cement is also beneficial in those products made from no-slump concrete mixtures. The use of slag cement reduces water demand and, therefore, allows for a reduction in water content needed to obtain the desired consistency (Fulton 1974).

6.4—Mortars and grouts

The use of slag cements typically improves the strength, permeability, flow, and cohesive characteristics of mortars and grouts. In these applications, slag cements are used in proportions similar to those used in the production of concrete.

The use of slag cement in the form of blended cements or separately blended with lime and portland cement for masonry mortars is well established. The same general properties found in concrete are also to be expected in mortars and grouts.

Special uses of slag cement in grouts for stabilization and solidification of waste materials were reported by Langton (1989). The combination of ultra-fine slag cement, having air-permeability fineness greater than 1000 m^2/kg, and portland cement or alkali salts are being used for grouting fine cracks in existing dams and stabilization of fine sands.

CHAPTER 7—REFERENCES

7.1—Referenced standards and reports

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation. Because some of these documents are revised frequently, generally in minor detail only, the user of this document should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Concrete Institute

116R	Cement and Concrete Terminology
211.1	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
212.3R	Chemical Admixtures for Concrete
301	Specifications for Structural Concrete
304R	Guide for Measuring, Mixing, Transporting, and Placing Concrete
308R	Guide to Curing Concrete
318	Building Code Requirements for Structural Concrete

ASTM International

C 94/C 94 M	Specification for Ready-Mixed Concrete
C 109/ C 109M	Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
C125	Terminology Relating to Concrete and Concrete Aggregates
C 162	Terminology of Glass and Glass Products
C 186	Test Method for Heat of Hydration of Hydraulic Cement
C 219	Terminology Relating to Hydraulic Cement
C 227	Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
C 403/ C403 M	Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
C 595	Specification for Blended Hydraulic Cements
C 666	Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 672	Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals

C 989   Specification for Ground Iron Blast-Furnace Slag for Use in Concrete and Mortars

C 1012   Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution

C 1073   Test Method for Hydraulic Activity of Ground Slag by Reaction with Alkali

C 1157   Performance Specification for Hydraulic Cement

C 1293   Test Method for Determination of Length Change of Concrete Due to Alkali-Silicate Reaction

C 1260   Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)

Canadian Standards Association
A23.5   Supplemental Cementing Materials and Their Use in Concrete Construction

These publications may be obtained from the following organizations:

American Concrete Institute
P. O. Box 9094
Farmington Hills, MI 48333-9094

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428

Canadian Standards Association
178 Rexdale Blvd.
Rexdale, Ontario M9W 1R3
Canada

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