

ACI 233R-17

# Guide to the Use of Slag Cement in Concrete and Mortar

Reported by ACI Committee 233



American Concrete Institute  
*Always advancing*



## **Guide to the Use of Slag Cement in Concrete and Mortar**

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at <http://concrete.org/Publications/DocumentErrata.aspx>. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised ACI Manual of Concrete Practice (MCP).

**38800 Country Club Drive**  
**Farmington Hills, MI 48331**  
**Phone: +1.248.848.3700**  
**Fax: +1.248.848.3701**

[www.concrete.org](http://www.concrete.org)

# Guide to the Use of Slag Cement in Concrete and Mortar

Reported by ACI Committee 233

R. Douglas Hooton, Chair

Thomas J. Grisinger<sup>†</sup>, Vice Chair

Thomas M. Greene, Secretary

Corina-Maria Aldea  
James M. Aldred  
Paul Brooks  
Russell T. Flynn  
William M. Hale  
Melissa O. Harrison

Alfred Kaufman  
Gerald D. Lankes  
Mark D. Luther  
V. M. Malhotra  
Gordon R. McClellan  
John M. Melander

H. Celik Ozyildirim  
Nicholas J. Popoff  
Henry B. Prenger  
Jan R. Prusinski  
Prasad R. Rangaraju  
Jay G. Sanjayan

Caijun Shi  
Marios N. Soutsos  
Lawrence L. Sutter  
Michael D. A. Thomas  
Jay E. Whitt  
Joe Denny Wills

## Consulting Members

Dennis Higgins

Donald W. Lewis

Derril L. Thomas

<sup>†</sup>Deceased.

Committee 233 expresses its gratitude to the late D. Elliot, former Chair of Committee 233.

*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.

## CONTENTS

### CHAPTER 1—GENERAL INFORMATION, p. 2

- 1.1—History, p. 2
- 1.2—Scope and objective, p. 3
- 1.3—Environmental considerations, p. 3
- 1.4—Production, p. 3

ACI Committee Reports, Guides, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

### CHAPTER 2—DEFINITIONS, p. 4

- 2.1—Definitions, p. 4

### CHAPTER 3—PROPERTIES AND PRODUCT TYPES, p. 4

- 3.1—Chemical and physical properties, p. 4
- 3.2—Hydraulic activity, p. 4
- 3.3—Factors determining cementitious properties, p. 5
- 3.4—Slag cement, p. 5
- 3.5—Blended cements, p. 6

### CHAPTER 4—STORAGE, HANDLING, AND BATCHING, p. 6

- 4.1—Storage, p. 6
- 4.2—Handling, p. 6
- 4.3—Batching, p. 6

### CHAPTER 5—PROPORTIONING CONCRETE CONTAINING SLAG CEMENT, p. 6

- 5.1—Proportioning with slag cement, p. 6
- 5.2—Ternary systems, p. 7
- 5.3—Use with chemical admixtures, p. 8

ACI 233R-17 supersedes ACI 233R-03(11) and was adopted and published September 2017.

Copyright © 2017, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

**CHAPTER 6—EFFECTS ON PROPERTIES OF FRESH CONCRETE, p. 8**

- 6.1—Workability, p. 8
- 6.2—Time of setting, p. 8
- 6.3—Air entrainment, p. 9
- 6.4—Bleeding, p. 9
- 6.5—Rate of slump loss, p. 10
- 6.6—Ternary systems, p. 10

**CHAPTER 7—EFFECTS ON PROPERTIES OF HARDENED CONCRETE AND MORTAR, p. 10**

- 7.1—Strength, p. 10
- 7.2—Modulus of rupture, p. 10
- 7.3—Modulus of elasticity, p. 11
- 7.4—Creep and shrinkage, p. 11
- 7.5—Influence of curing on performance, p. 12
- 7.6—Color, p. 12
- 7.7—Effects on temperature rise in mass concrete, p. 12
- 7.8—Permeability, p. 13
- 7.9—Resistance to sulfate attack and delayed ettringite formation, p. 14
- 7.10—Reduction of expansion due to alkali-silica reaction, p. 15
- 7.11—Resistance to freezing and thawing, p. 16
- 7.12—Resistance to deicing chemicals, p. 16
- 7.13—Resistance to the corrosion of reinforcement, p. 17
- 7.14—Carbonation, p. 17
- 7.15—Ternary systems, p. 17

**CHAPTER 8—SLAG CEMENT APPLICATIONS, p. 18**

- 8.1—Introduction, p. 18
- 8.2—General use in ready mixed concrete, p. 18
- 8.3—Concrete products, p. 18
- 8.4—Mortars and grouts, p. 18
- 8.5—Controlled low-strength material, p. 18
- 8.6—Environmental structures, p. 18
- 8.7—Heat resistance, p. 19
- 8.8—High-strength, high-performance concrete, p. 19
- 8.9—Industrial floors, p. 19
- 8.10—Lightweight concrete, p. 19
- 8.11—Marine structures, p. 19
- 8.12—Mass concrete, p. 20
- 8.13—Mine backfill, p. 20
- 8.14—Pavements and bridges, p. 20
- 8.15—Roller-compacted concrete, p. 20
- 8.16—Soil stabilization, p. 20
- 8.17—Tilt-up, p. 21
- 8.18—Waste stabilization, p. 21
- 8.19—Miscellaneous, p. 21

**CHAPTER 9—SUSTAINABLE DEVELOPMENT, p. 21**

- 9.1—Slag cement and sustainability, p. 21
- 9.2—High volume slag cement use in concrete, p. 21
- 9.3—Life-cycle inventory for slag-cement concrete, p. 21
- 9.4—Reflectance, p. 22
- 9.5—Federally-funded projects, p. 23
- 9.6—Service life, p. 23
- 9.7—Green building rating systems, p. 23

**CHAPTER 10—REFERENCES, p. 23**

Authored documents, p. 24

**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 m<sup>3</sup> (863,000 yd<sup>3</sup>) 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. Currently, slag

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

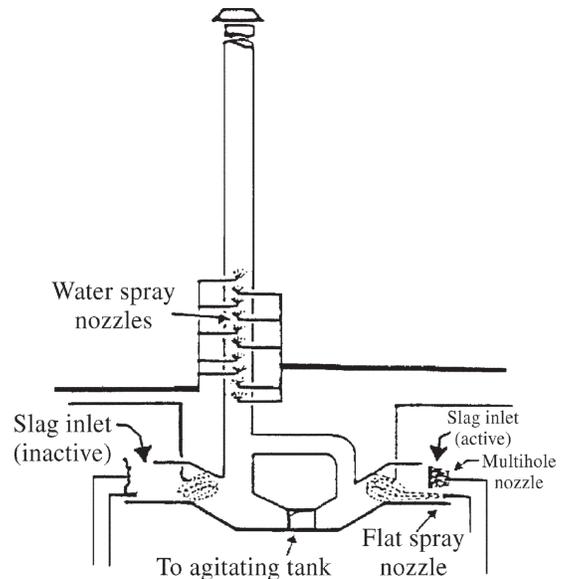


Fig. 1.4.2a—Configuration of blast-furnace slag water granulator to include steam-condensing tower (Hogan and Meusel 1981).

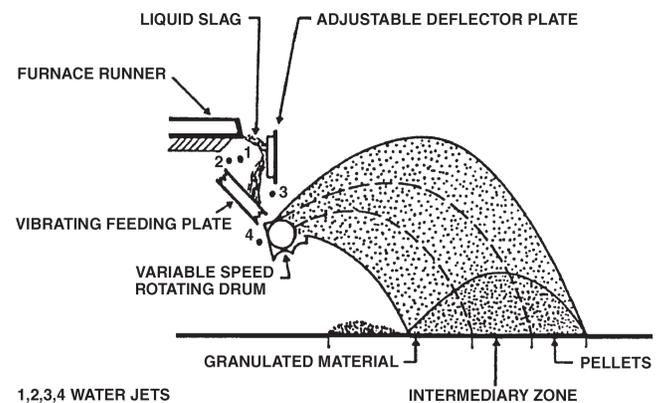


Fig. 1.4.2b—Blast-furnace slag palletization process, using a minimum of water usually applied at the feed plate (Hogan and Meusel 1981).

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

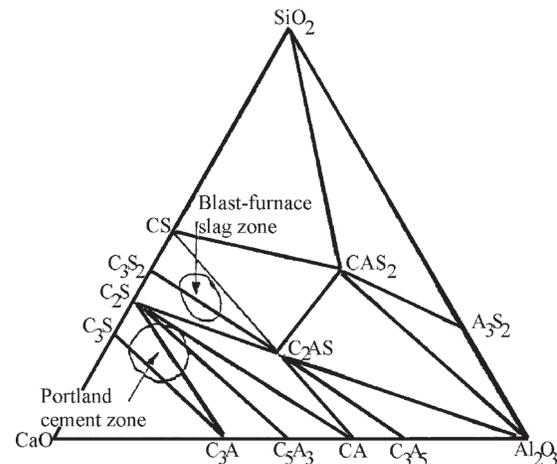
The chemical composition of blast-furnace slag is determined by that of the ore, fluxing stone, and impurities in the coke charged into the blast furnace. Typically, silica, calcium, aluminum, magnesium, and oxygen constitute 95 percent or more of the blast-furnace slag. Table 3.1 indicates the chemical 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 <sub>2</sub>	32 to 42
Al <sub>2</sub> O <sub>3</sub>	7 to 16
CaO	32 to 45
MgO	5 to 15
S	0.7 to 2.2
Fe <sub>2</sub> O <sub>3</sub>	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-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> (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 (Smolezyk 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 ( $\text{Ca}(\text{OH})_2$ ) 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

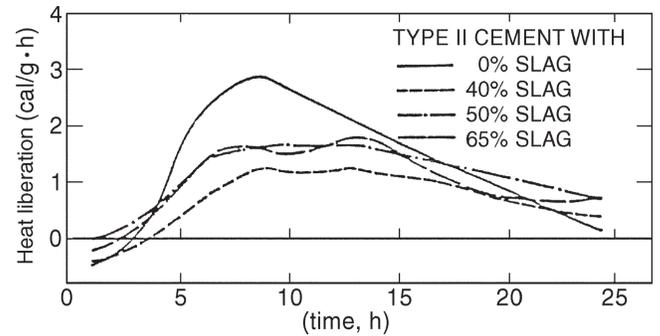


Fig. 3.2b—Rate of heat liberation of cements with and without slag cement at 80°F (27°C) (Roy and Idorn 1982).

- 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 has an optional 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; Hooton 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) ([Aitein 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 heat generation 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  $m^2$ /

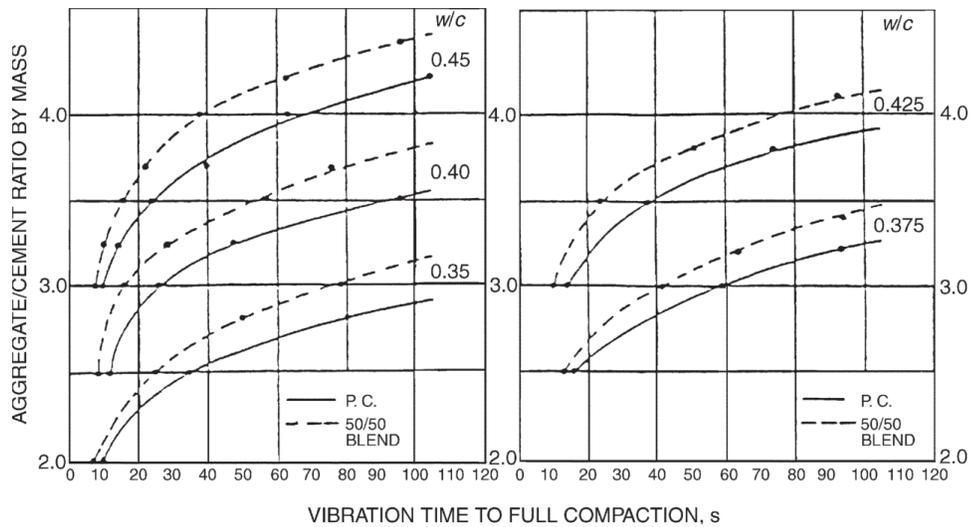


Fig. 6.1a—Relationship between response to vibration of concrete mixtures made with portland cement and mixtures containing 50 percent slag cement (Fulton 1974).

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

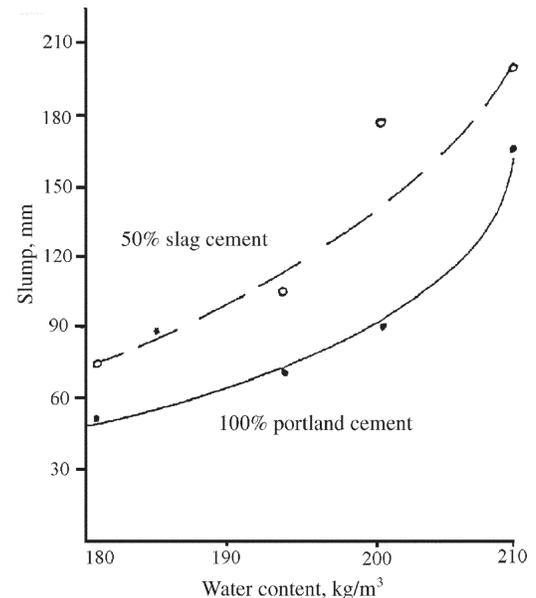


Fig. 6.1b—Effect of water content on slump of concrete mixtures with and without slag cement (Meusel and Rose 1983) (Note: 25.4 mm = 1 in.; 1 kg/m<sup>3</sup> = 1.69 lb/yd<sup>3</sup>).

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

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.

### 6.5—Rate of slump loss

Meusel and Rose (1983) indicated that concrete containing slag cement at 50 percent 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).

### 6.6—Ternary systems

Slag cement can be used in ternary systems in conjunction with other supplementary cementitious materials (SCMs). When slag cement is used in ternary systems with silica fume, the amount of silica fume can be reduced compared to a mixture of equivalent durability with portland cement and silica fume. This will improve the workability and finishability of the concrete. The amount of each cementitious material will effect time of set, bleeding, and slump loss similar to the changes experienced in binary mixtures containing slag cement.

## CHAPTER 7—EFFECTS ON PROPERTIES OF HARDENED CONCRETE AND MORTAR

### 7.1—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 (1 to 3 days) and increased strength at later ages (7 days and beyond) (Hogan and Meusel 1981). Use of Grade 100 slag cements 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 percent portland cement mixture.

The extent to which slag cement affects strength depends on the slag activity index of the specific slag cement and the fraction in which it is used in the mixture. 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, as well as curing conditions. As seen in Fig. 7.1a, 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

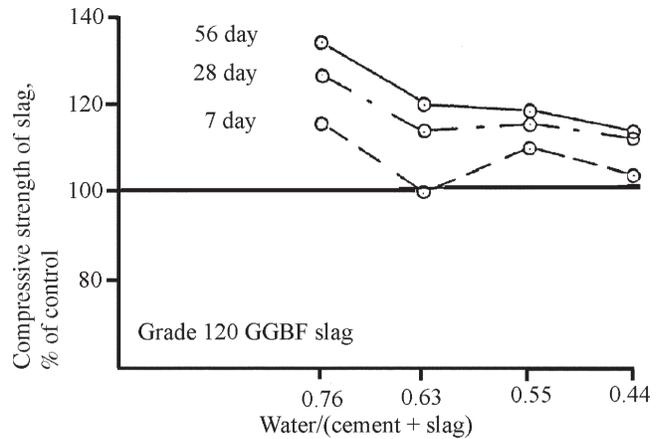


Fig. 7.1a—Effect of  $w/cm$  on compressive strength of mixtures containing 50 percent slag cement, expressed as a percentage of mixtures made with only portland cement (Meusel and Rose 1983).

containing slag cement responds well to elevated temperature curing conditions (Roy and Idorn 1982). 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. 7.1b. When highly active slag cements have been used, the greatest 28-day strengths are found with blends as high as 65 percent 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 7.1c compares compressive strength development of various blends of slag cement and portland cement with a portland-cement mixture only.

### 7.2—Modulus of rupture

Of great 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. 7.2). 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.

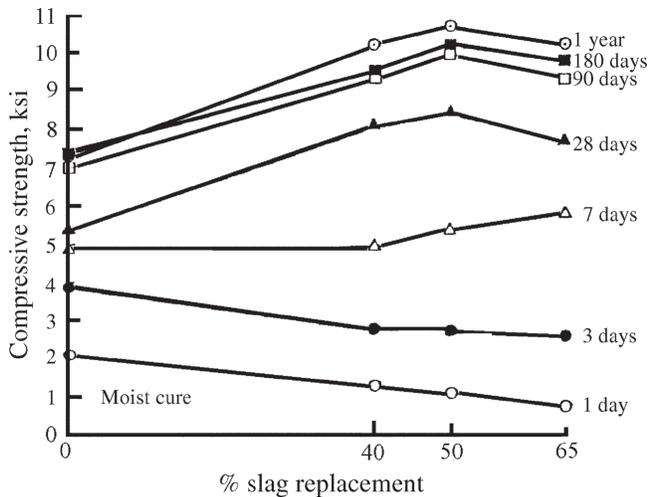


Fig. 7.1b—Influence of slag cement on mortar cube compressive strength (Hogan and Meusel 1981). (Note: 1 ksi = 6.89 MPa.)

### 7.3—Modulus of elasticity

Research conducted with four different slag cement sources by Brooks et al. (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.

### 7.4—Creep and shrinkage

As discussed in the following paragraphs, 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 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 et al. (1986) tested concrete made with 35 percent 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 et al. (1992) investigated the time-dependent properties of four different slag sources and varying slag cement

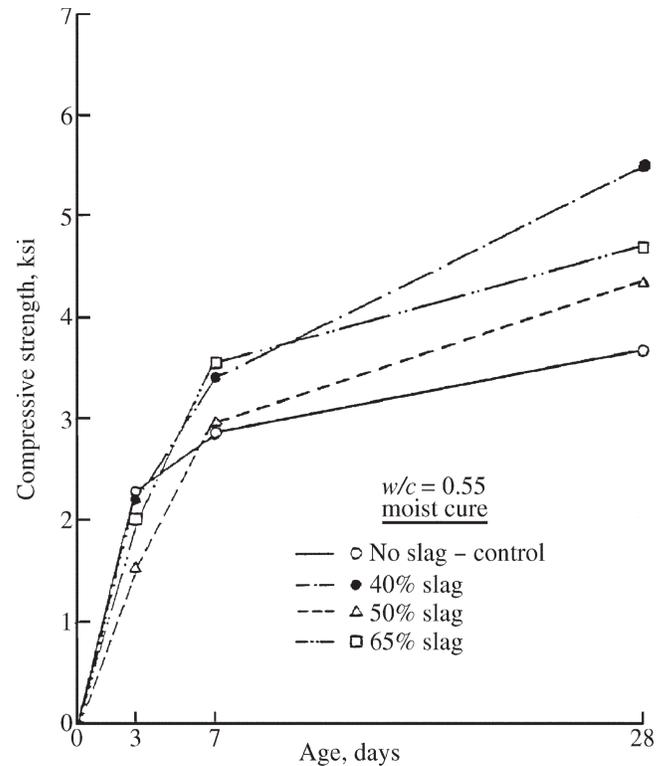


Fig. 7.1c—Compressive strength of concrete containing various blends of slag cement compared with concrete using only portland cement as a cementitious material (Hogan and Meusel 1981). (Note: 1 ksi = 6.89 MPa.)

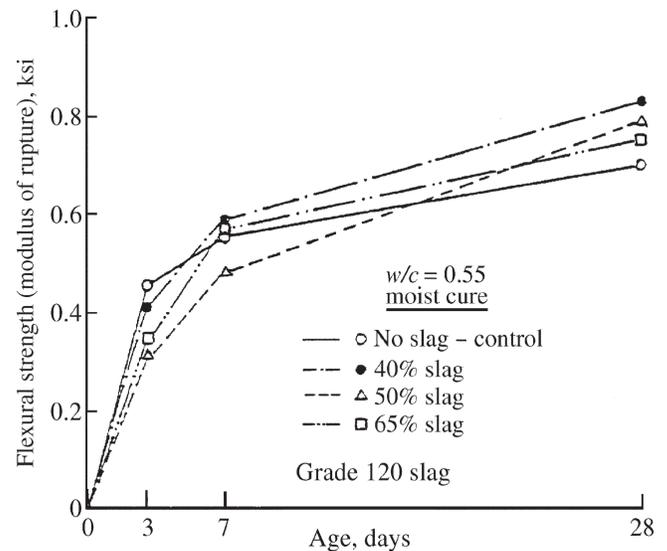


Fig. 7.2—Flexural strength (modulus of rupture) of concrete containing various blends of slag cement, compared with concrete using only portland cement as cementitious material (Hogan and Meusel 1981). (Note: 1 ksi = 6.89 MPa.)

replacement levels between 30 and 70 percent 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 percent slag cement showed less drying shrinkage than the 100 percent portland cement mixture (Lankard 1992). The combination of 30 percent 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 percent portland cement mixtures. Evaluating roller-compacted concrete, Togawa and Nakamoto (1989) found that the use of slag cement reduced shrinkage.

Tazawa et al. (1989) concluded that the drying shrinkage and creep of slag cement concrete was less than that of 100 percent portland-cement concrete when standard 28-day curing was used. The total cementitious material content in this concrete ranged from 455 to 624 lb/yd<sup>3</sup> (270 to 370 kg/m<sup>3</sup>), and the slag cement ranged in Blaine fineness from 441 m<sup>2</sup>/kg to 585 m<sup>2</sup>/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.

Published data were compiled by Hooton et al. (2009), and it was found that the drying shrinkage of concrete containing slag cement is approximately the same as a similar concrete not containing slag cement. When corrected to a constant paste content, slag cement concrete shrinks approximately 3 percent less than portland-cement concrete. This is true independently of the slag cement content and *w/c* of the concrete mixture over the ranges typically used in concrete. Such a small difference is not considered significant. The data related to the effect on shrinkage of intergrinding gypsum in slag cement were limited, but indicated that optimizing gypsum contents of the entire cementitious binder will reduce drying shrinkage (Hooton et al. 2009).

An opportunity 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.

### 7.5—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 3 days. Conversely, Fulton (1974) reports that concrete containing more than 30

percent 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 308R.

### 7.6—Color

Slag cement is considerably lighter in color than gray portland cement and will produce a lighter color in concrete after curing. In certain operations, up to 30 percent 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, 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.

### 7.7—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. 7.7, where in-place measurements were reported by Soutsos et al. (2016) comparing 1.4 m (4.6 ft) cubes of both 30 and 50 MPa (4500 and 6000 psi) concretes made with 100 percent portland cement to concrete with 50 percent slag cement; concrete cubes were cast both in warm

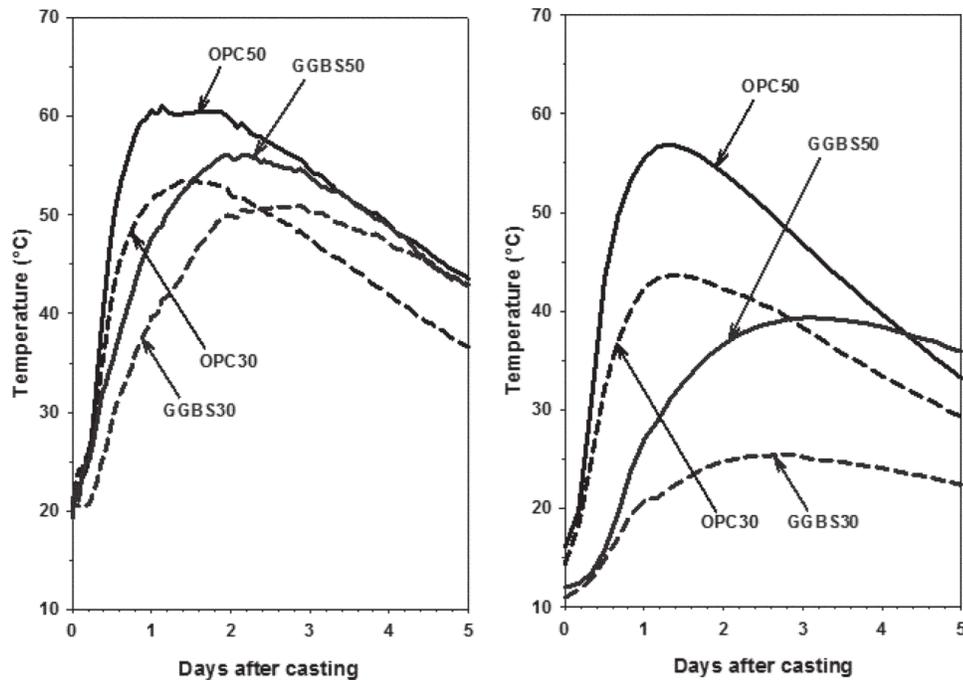


Fig. 7.7—Temperature rise of 4.6 ft (1.4 m) concrete blocks cast in warm (left) and cool (right) weather with 0 and 50 percent slag cement (adapted from Soutsos et al. 2016). Note: 30 and 50 refer to the concrete design strengths in MPa (4350 and 7250 psi); degrees Fahrenheit = (degrees Celcius  $\times$  1.8) + 32.

and cool weather. 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 C186. The mixtures with slag cement produced the greater cumulative heat (Bamforth 1980; Hogan and Meusel 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.

### 7.8—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). The permeability of concrete depends on porosity and pore-size distribution (Mehta 1980). The reduction in pore size due to slag cement is seen in Fig. 7.8a, which compares the pore-size distribution in paste with and without slag cement. Where slag cements are used, reduction in the pore size occurred

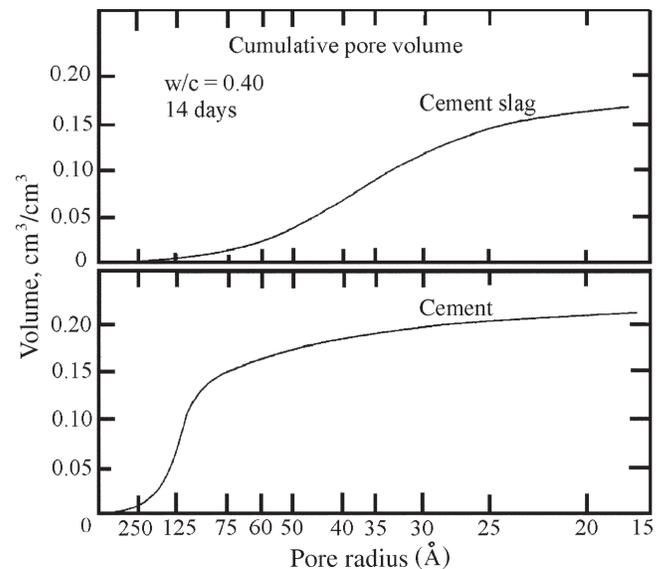


Fig. 7.8a—Comparison of pore-size distribution of paste containing portland cement and paste containing 40 percent slag and 60 percent portland cement, tested by mercury intrusion (Roy and Parker 1983). (Note: cm<sup>3</sup>/cm<sup>3</sup> = in.<sup>3</sup>/in.<sup>3</sup>; 1 Å = 10<sup>-10</sup> m.)

before 28 days after mixing (Bakker 1980; Mehta 1980; Roy and Idorn 1982). Another example of reduced penetrability is shown in Fig. 7.8b (Smolczyk 1977), where concrete of varying w/cm and slag cement content were evaluated for chloride diffusion over a period of 2 years.

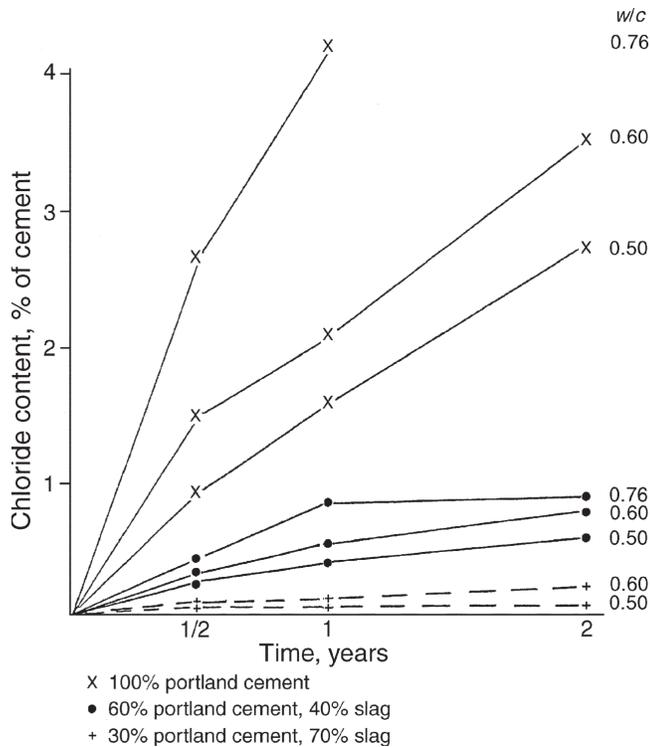


Fig. 7.8b—Results of chloride content in 0.8 to 1.6 in. (20.3 to 40.6 mm) deep layers in concrete beams stored in 3.0 molar solution of NaCl (Smolczyk 1977).

### 7.9—Resistance to sulfate attack and delayed ettringite formation

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 cement proportion exceeds 50 percent 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 percent blends of slag cement with Type I portland cement containing up to 12 percent  $C_3A$  have sulfate resistance equivalent to that of Type V cements. The slag cement was reported to have 7 percent  $Al_2O_3$  (Chojnacki 1981). As reported by Hooton and Emery (1990), a minimum amount of slag cement is required to provide high sulfate-resisting properties to concrete. Their results, using ASTM C1012/C1012M, indicate that this minimum would be 50 percent or greater when used with Type I portland cement having a  $C_3A$  content up to 12 percent, as long as the  $Al_2O_3$  content of the slag cement was lower than 11 percent (Fig. 7.9a). When the  $Al_2O_3$  content of the slag cement is above 11 percent, slag replacements of 60 to 70 percent may be required. In addition, in such slag cements, some of the alumina becomes active at early ages and competes with the aluminates in the portland cement for cement sulfate. This can end up undersulfating the cementitious system so that monosulfoaluminate is the predominant phase in the hardened binder, and when exposed to an external source of sulfates, the monosulfoaluminate will form ettringite, potentially resulting in damage to the hardened concrete. Therefore, for sulfate resistance, it

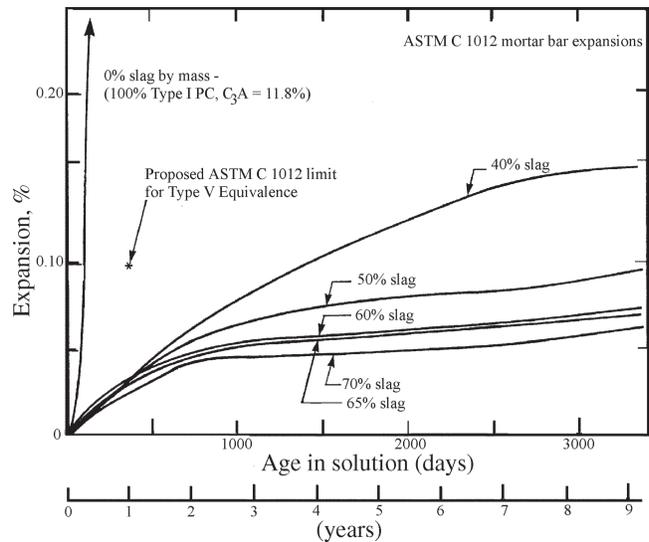


Fig. 7.9a—Effect of various slag cement replacement levels on expansions in 50,000 mg/L (50,000 ppm)  $SO_4$  as  $Na_2SO_4$  (slag  $Al_2O_3 = 8.4$  percent) (Hooton and Emery 1990).

has been found to be beneficial to intergrind calcium sulfate with slag, having an alumina content above 11 percent with more calcium sulfate required with increasing slag alumina content. Interground calcium carbonate has also been found to help (Higgins 2003). Combinations of calcium carbonate and calcium sulfate have been shown to be effective to mitigate the effects of slag with an  $Al_2O_3$  content of 15 percent when used in a blended cement (Ogawa et al. 2009). In ACI 318, it is required that ASTM C1012/C1012M testing be performed to verify that expansion limits will be met when using combinations of hydraulic cement and slag cement.

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

a) 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. Where the alumina content of the slag cement is less than 11 percent, increased sulfate resistance was found, regardless of the  $C_3A$  content of the portland cement where blends between 20 and 50 percent slag cement were used (Lea 1971).

b) 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.

c) 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 alkalis 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

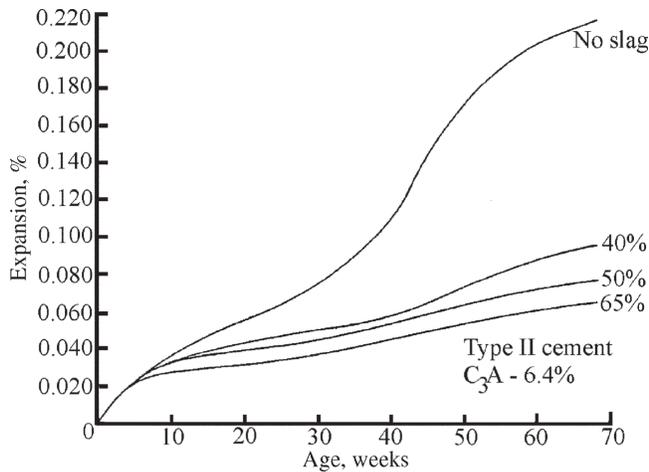


Fig. 7.9b—Sulfate resistance of mortar bars, Wolochow test, Type II (Hogan and Meusel 1981).

mortar bars with either Type II or Type V cement; the results for the mortar made with Type II cement are illustrated in Fig. 7.9b.

Another form of sulfate attack is delayed ettringite formation (DEF), which may occur in concrete that is exposed to elevated temperature at an early age. DEF does not require an external source of sulfate. Many researchers have demonstrated that slag cement, when used at sufficiently high levels of cement replacement (greater than or equal to 35 percent), is an effective measure for controlling damaging expansion due to DEF (Ghorab et al. 1980; Lewis 1996; Ramlochan et al. 2004b).

### 7.10—Reduction of expansion due to alkali-silica reaction

Use of slag cement as a partial replacement for portland cement is known to reduce the potential expansion of concrete due to alkali-silica reaction (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 et al. 1950). Since that time, there have been more than 100 publications dealing with the effect 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 percent 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 percent 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 percent slag cement (Cornielle 1988; Heijnen et al. 1996); however, there were no reported cases of ASR in concrete containing 50 percent

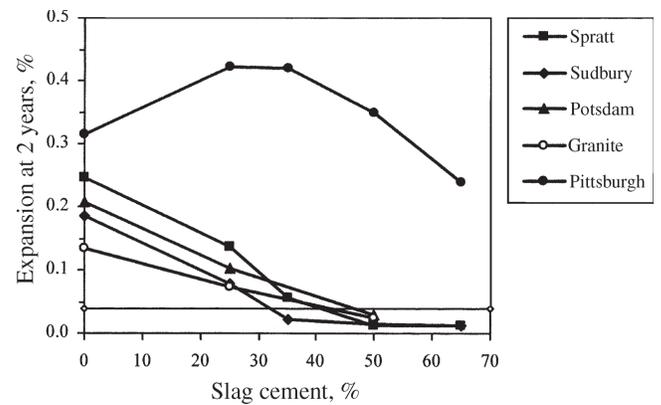


Fig. 7.10a—Expansion of concrete prisms with various aggregates (Thomas and Innis 1998).

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 et al. 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 C1293 concrete prism test. Figure 7.10a shows the expansion of concrete prisms after 2 years of storage over water (that is, approximately 100 percent relative humidity) at 100.4°F (38°C). Between 35 and 50 percent slag cement was required to control the expansion of concrete containing alkali-silica-reactive aggregate to less than 0.04 percent at 2 years. Slag cement was not effective, however, in controlling the expansion of alkali-carbonate reactive (ACR) aggregate. The same paper reports that low-alkali cement (0.50 percent Na<sub>2</sub>O equivalent) was also ineffective in controlling the expansion of concrete containing this ACR aggregate. The combination of slag cement with relatively small amounts of silica fume conferred an additional measure of control to expansion caused by ASR. Hooton et al. (2013) has shown both 50 percent slag cement and 25 percent slag together with 3.8 percent silica fume to be effective in preventing deleterious expansion and cracking of large concrete beams (2.0 x 2.0 x 6.5 ft [0.6 x 0.6 x 2.0 m]), as shown in Fig. 7.10b as well as in sidewalk sections after 20 years. Using the same reactive aggregate, pavement sections with 35 and 50 percent slag cement, as well as ternary slag cement-silica fume mixtures with as little as 25 percent slag cement together with 4 percent silica fume, have been effective in preventing cracking and expansion after 10 years of exposure (Hooton et al. 2008).

ASTM C989/C989M reports that where slag cements are used in quantities greater than 40 percent of the total cementitious material, reduced expansion due to the ASR is found with cement having alkali contents up to 1.0 percent. Hogan and Meusel (1981) report that where slag cement contents are used in percentages from 40 to 65 percent of total cementitious material, expansion is virtually eliminated when tested in accordance with ASTM C227 (Fig. 7.10c). Their test used highly reactive borosilicate glass to obtain maximum expansion. Similar results were reported

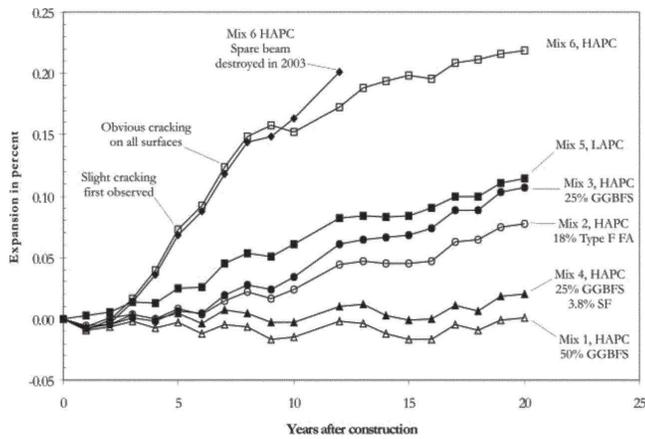


Fig. 7.10b—Long-term expansions of 2 ft x 2 ft x 6.5 ft (0.6 m x 0.6 m x 2.0 m) unreinforced concrete beams made with ASR aggregate (spratt) in outdoor exposure (Hooton et al. 2013).

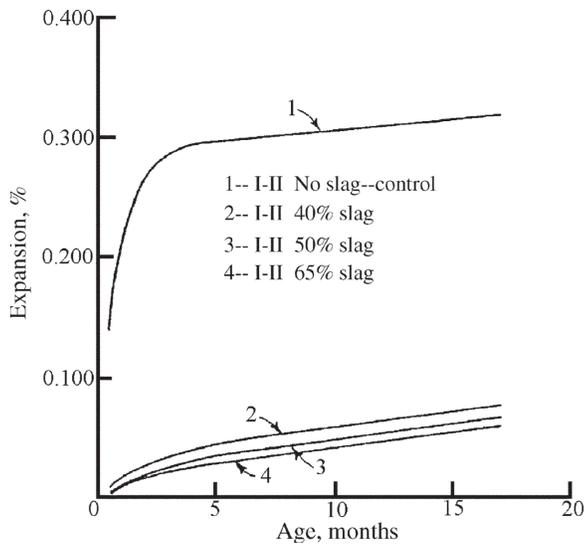


Fig. 7.10c—ASTM C227 potential alkali-aggregate reactivity for various slag replacements (Hogan and Meusel 1981).

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 et al. (1989). After 2 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 percent slag cement appear to be effective in reducing the potential of ASR but not ACR.

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 C1260 mortar-bar test. These data were collected by the Mid-Atlantic Regional Technical Committee (1993) and used in the development of a guide, but the test data are unpublished. After evaluating several slag cements from the eastern seaboard, these states tended to require at least 40 percent slag cement

in concrete containing a potentially reactive aggregate where slag cement was used as the method of mitigation.

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

- Reduced permeability
- Change of the alkali-silica ratio
- Dissolution and consumption of the alkali species
- Direct reduction of available alkali in the system
- Reduction of calcium hydroxide needed to support the reaction

### 7.11—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 percent 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 C666/C666M (Procedure A) (Hogan and Meusel 1981). Similar results were found by Malhotra (1980) using various percentages of slag cement with portland cement.

### 7.12—Resistance to deicing chemicals

Although some laboratory tests with Type IS cement indicate less resistance to deicing salts, research has 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 percent slag cement and 50 percent portland cement (Hogan and Meusel 1981), or slag cement percentages exceeding 35 percent (Afrani and Rogers 1994; Boyd and Hooton 2007). Another laboratory and field study (Bouzoubaa et al. 2008) showed that concrete with 35 percent slag cement performed poorly in the ASTM C672/C672M laboratory test, but performed well in a modified version of this test and in the field after four winters.

Research conducted with slabs cast on ground and using ASTM C672/C672M tests, all using exterior residential concrete mixtures containing approximately 516 lb/yd<sup>3</sup> (306 kg/m<sup>3</sup>) of cementitious material and with ASTM C989 Grade 100 and Grade 120 slag cements, identified 25 percent slag cement to be an optimum amount for scaling resistance. Concrete with 25 percent 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 approximately 50 percent slag cement content (Luther et al. 1994). ACI 301 and ACI 318 allow up to 50 percent 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. In addition, occurrences of scaling are mainly restricted to hand-finished flatwork such as driveways and sidewalks, and scaling is much less likely on formed or slipformed surfaces. 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. The curing regime was also found to make a measurable difference in the field scaling resistance of a 50 percent slag mixture, with the application of a curing compound reducing the degree of scaling to almost nothing when compared to plastic-covered wet-burlap curing (Boyd and Hooton 2007).

### 7.13—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, 1983; Fulton 1974; Mehta 1980; Roy 1989; Rose 1987; 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, 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 high-quality concrete reduces concrete permeability, thus reducing the penetration of chloride ions and the depth of carbonation that promote corrosion of steel. Thomas et al. (2008) reported results for concrete blocks (1 x 1 x 3 ft [300 x 300 x 900 mm]) containing 0, 25, 45, and 65 percent slag cement after 25 years of exposure in the tidal zone of the U.S. Corps of Engineers' Marine Exposure Site on Treat Island, near Eastport, ME. Chloride profiles for concrete with  $w/cm = 0.40$  (Fig. 7.13) shows significantly reduced chloride ion penetration in the concrete containing slag cement, especially at the higher replacement levels (45 and 65 percent).

### 7.14—Carbonation

When  $CO_2$  from the atmosphere penetrates concrete, it will react with the main cement hydration products, resulting in a drop in the pH of the concrete pore solution from above pH 13 to somewhere in the region of pH 8. If the carbonation front reaches the embedded steel reinforcement, the loss of alkalinity will result in the loss of the protective passive layer and the corrosion of the steel will be initiated. If there is sufficient oxygen and water available in the concrete, the steel will corrode, eventually leading to damage to the concrete. Carbonation-induced corrosion is relatively rare and cases are mainly confined to low-strength, poorly-cured concrete with low depths of cover over the steel.

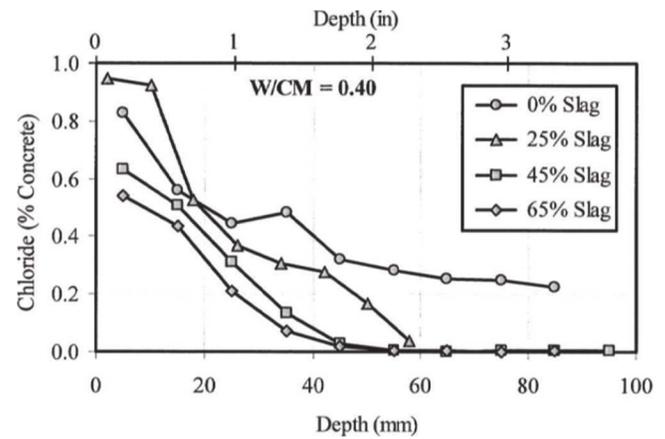


Fig. 7.13—Chloride profile for concrete at  $w/cm = 0.40$  after 25 years in marine exposure (Thomas et al. 2008). (Note: 1 in. = 25.4 mm.)

An extensive review of carbonation studies by Parrott (1987) concluded that for a given  $w/cm$ , the rate of carbonation increases as the amount of SCM increases. This is due to the reduced amount of  $Ca(OH)_2$  in concrete containing pozzolans or slag cement. Much of the data available, however, indicate that the rates of carbonation are similar for concretes that are proportioned to achieve the same 28-day compressive strength.

A study on the effects of slag cement on the carbonation of laboratory concretes and field structures showed that the depth of carbonation depended mainly on the slag cement content and the micro-climate (Osborne 1986, 1989). In dry, sheltered environments, the depth of carbonation increased significantly with slag cement content, especially at 70 or 80 percent slag, and Osborne (1989) recommends that the slag cement replacement level be restricted to 50 percent for slender reinforced concrete elements exposed to such conditions. Higher levels of slag cement, however, can be used when the concrete is exposed to moisture during service and where chemical resistance to chlorides, sulfates, and seawater is required.

### 7.15—Ternary systems

Ternary cements are blends of portland cement with two supplementary cementitious materials (SCMs). There has been an increase in the use of ternary blends in the past decade, especially blends where the two SCMs are either silica fume plus fly ash or silica fume and slag cement. A factory blend produced by intergrinding portland-cement clinker, silica fume (3 to 5 percent), slag cement (20 to 25 percent), and gypsum has been available in Canada since 1999 (Thomas et al. 2007). Extensive testing of this product has shown that cement has equivalent early-age strength and improved later-age strength compared to portland cement produced from the same clinker; additionally, the ternary blend showed much improved chloride and sulfate resistance, and the ability to control alkali-silica reaction (ASR).

Bleszynski et al. (2000, 2002) also demonstrated significant improvements regarding chloride resistance and ASR

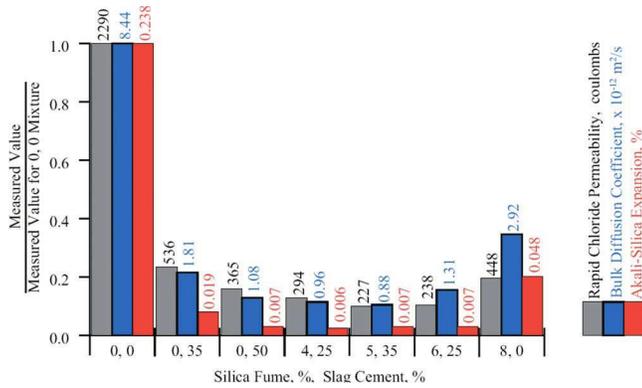


Fig. 7.15—Rapid chloride permeability, bulk diffusion coefficient, and expansion due to ASR test results for 2-year-old concrete samples with a w/cm of 0.42 (from Bleszynski et al. [2000, 2002] and Thomas et al. [2007]).

control when ternary blends containing silica fume and slag cement were used, as shown in Fig. 7.15.

## CHAPTER 8—SLAG CEMENT APPLICATIONS

### 8.1—Introduction

Some combinations of slag cement and portland cement may be used in all portland-cement-based concrete, mortar, and grout applications. Also, combinations of slag cement feature increasingly in ternary and quaternary (that is, four cementitious materials) mixtures. The optimum slag-cement percentage varies with the application, selection of other cementitious materials and combinations, performance requirements, and other normal factors that apply to portland-cement concrete.

Where available, slag cement concrete is supplied using normal batching and delivery, such as from ready mixed, paving and other site-batched, precast/prestressed, and concrete-products plants. Slag cement is added to the concrete mixture either as a separate cementitious material (from a separate material silo) or as a component in blended cement.

### 8.2—General use in ready mixed concrete

In the early 1980s, in the Mid-Atlantic states where **ASTM C989/C989M** slag cement was first produced, a 50 percent replacement was commonly employed during warm weather (Wood 1981), and lower replacements would be used in cooler weather. As slag cement availability increased, more variety in levels of slag cement replacement was seen. Depending on application, specification requirements, and weather, slag cement replacements can now be optimized through the 20 to 80 percent range band (Slag Cement Association 2002a).

### 8.3—Concrete products

The slag cement replacement level in precast concrete products is usually limited by the strength needed at the end of the curing cycle (typically 15 to 20 hours). Without re-proportioning the mixture, at room-temperature curing, relative to 100 percent portland-cement concrete, 1-day strength is usually lowered depending on slag cement fineness and

w/cm. With such limited curing, slag-cement replacement tends to be limited to approximately 30 percent.

With heat curing, the replacement can be increased. Concrete containing slag cements responds favorably to elevated curing temperatures and can achieve 1-day strength similar to plain portland-cement concrete (Hogan and Meusel 1981). Using accelerated curing at 150°F (65°C), 18-hour strengths exceeding 5800 psi (40 MPa) were obtained using slag cement in ternary mixtures with silica fume (Titherington and Hooton 2004). Slag cement is also beneficial in those products made from no-slump concrete mixtures. The use of slag cement may reduce water demand and, therefore, allow a reduction in water content needed to obtain the desired consistency (Fulton 1974). Typically, the water demand is close to that of portland-cement mixtures.

### 8.4—Mortars and grouts

Slag cements typically improve 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. **ASTM C270** references **ASTM C595/C595M** Type IS blended slag cements. **ASTM C476** specification for grout has provisions for the use of **ASTM C595/C595M** IS blended cements and **ASTM C989/C989M** is the specification for slag cement used in concrete and mortar. The combination of ultra-fine slag cement, having air-permeability fineness greater than 1000 m<sup>2</sup>/kg, and portland cement or alkali salts are being used for grouting fine cracks in existing dams and stabilization of fine sands.

### 8.5—Controlled low-strength material

Controlled low-strength material (CLSM) mixtures, also known as flowable fill in the United States, have historically employed fly ash as the main binder, combined with a minor amount of portland cement (such as 50 lb/yd<sup>3</sup> [30 kg/m<sup>3</sup>]), with total cementitious materials contents in the 100 to 400 lb/yd<sup>3</sup> (60 to 240 kg/m<sup>3</sup>) range, and with fly ash comprising 50 to 80 percent of the cementitious mass. CLSM has been made with slag cement, and in the same general total cementitious materials range and with most of the cementitious component being the slag cement. Slag cement can also be used in conjunction with fly ash or cement-kiln dust. Typically, with CLSM, a maximum strength at some age is specified. Because slag cement continues to develop strength at later ages, evaluating ultimate strength is important in developing mixture proportions. **ACI 229R** discusses the use of slag cement in CLSM.

### 8.6—Environmental structures

Slag cement concrete has been used commonly in water-treatment, wastewater-treatment, and chemical-processing plants, as well as petroleum refineries. An evaluation of 23 wastewater-treatment plants built of high-slag-cement

content concrete from 1958 to 1963, all exposed to frost environment along the German North Sea coast, found the concrete to be durable (Lang and Geisler 1996). Examples of such projects include Newtown Creek wastewater treatment facility in New York, and the Croton water filtration facility in New York, where 70 percent slag cement was used.

Environmental structures often have very specific requirements, and slag cement can be used to meet these needs. These may include combinations of strength; low heat; low shrinkage; low permeability; and resistance to alkali-silica reaction (ASR), sulfate attack, and a specific combination of chemicals. Generally, 30 to 70 percent slag cement is selected when multiple needs overlap. Slag-cement concrete is also commonly used at precast plants in making concrete pipe, culverts, and related environmental structures.

### 8.7—Heat resistance

Calcium aluminate cements have good heat resistance, but when used as the sole cementing material, undergo a conversion reaction of initial hydrates that results in significant loss of strength. Research in the United Kingdom indicated that combinations of calcium-aluminate with slag cement (as the minor component, or in equal portion) could stabilize the long-term hydration products and improve durability (Osborne and Singh 1995). Some industrial floors in Gary, IN, have used calcium aluminate cement as the main binder in a concrete mixture that otherwise would look like a normal 4000 or 5000 psi (28 or 35 MPa) mixture. Typically, the main binder is replaced with slag cement in the 30 to 50 percent range. The concrete is ready mixed, but mixers should be dedicated to the project and all trace of portland cement residue should be meticulously cleaned from the mixers before calcium-aluminate cement use, because mixtures of portland and calcium aluminate cement can result in flash set.

In portland-cement-based concrete, a 40 percent slag cement replacement demonstrated improved resistance to spalling from jet-exhaust blast (Robins and Austin 1995). In general, replacement of portland cement with slag cement can improve resistance to heat for moderate exposures, in part because free lime content in the hardened concrete is reduced and strength is usually increased.

### 8.8—High-strength, high-performance concrete

For high-strength concrete, slag cement affords significant strength increase over 100 percent portland-cement concrete across a broad replacement range, all other factors being equal. In the United States, strengths exceeding 10,000 psi (70 MPa) have been supplied for major projects. Of note is the 10,000 psi (70 MPa) tower of the Maumee River Bridge constructed in Toledo, OH, area in the early 2000s, where a 50 percent slag-cement mixture was used.

In recent years, it is increasingly common to see ternary mixtures that also include fly ash or silica fume (Slag Cement Association 2002a). In the mid-2000s, the foundation of the Trump Tower in Chicago, IL, employed a high-strength, self-consolidating concrete in the mass-concrete foundation. The concrete included both silica fume and slag cement. The four

super columns in Reliant Stadium, Houston, TX, contain a ternary mixture incorporating slag cement and Class C fly ash that achieved strengths exceeding 18,000 psi (124 MPa).

In Toronto, ON, Canada, slag cement plus silica fume ternary cementitious mixtures have been used since 1985 to produce numerous 10,000 and 12,500 psi (70 and 85 MPa) specified strength concretes, typically also requiring 3000 psi (20 MPa) at 11 hours, for high-rise columns and elevator cores using jump forms (Bickley et al. 1991, 1994; Hooton 2000).

In Japan, slag cements with fineness up to 1000 m<sup>2</sup>/kg have been used in high-strength concrete for many years, and strengths exceeding 14,500 psi (100 MPa) have been achieved (Nagataki 1996). Blended cements containing normally ground, or very-fine fractions of, slag cement have achieved over 10,000 psi (70 MPa) (Marushima et al. 1993).

Throughout much of Europe, many blended cements contain cementitious slag, and these are often used in high-strength structures. Research has also demonstrated that concrete strengths in the 10,000 to 14,500 psi (70 to 100 MPa) range can be achieved with various cementitious slag finenesses, accompanied with lowered heat and permeability (Swamy et al. 1993).

Wear-resistant concrete using slag cement with silica fume has developed strength exceeding 17,500 psi (121 MPa) (Holcim (US) Inc. 2002).

### 8.9—Industrial floors

Normal-strength slag-cement concrete has been used in industrial floors. Generally, it is somewhat easier to finish slag-cement concrete with replacements up to approximately 50 percent of portland cement, due to reduced tool drag. Also, hardened slag-cement concrete presents a lighter shade of gray, or even white, as compared to a similar 100 percent portland-cement mixture.

When reduced drying shrinkage is needed, the higher strength of slag-cement concrete can facilitate obtaining lower paste content.

### 8.10—Lightweight concrete

Slag cement can be used in lightweight concrete. The lower specific gravity of slag cement (approximately 2.90) relative to that of portland cement (approximately 3.15) confers a small benefit toward achieving reduction in hardened-concrete density. Also, at a strength-optimized replacement, the greater strength often achieved by use of the slag cement presents the opportunity to use less paste and commensurately increased lightweight aggregate volume in the mixture. An example project is the Kone Center in Moline, IL (Slag Cement Association 2013).

### 8.11—Marine structures

In the Netherlands, concrete using high amounts of cementitious slag, delivered via blended cement, has been used in marine structures since 1917. A 65 to 75 percent cementitious slag content in blended cement is common (Bijen 1996). Such concrete has also been used in the Middle East (Bijen 1996). In the United Kingdom, a study of 70 percent cementitious slag concrete in a tidal marine environ-

ment showed a need to use air-entrained concrete to achieve durable surfaces when frost exposure is present (Osborne 1998). In Germany, marine structures constructed in the late 1930s and early 1940s were studied in the early 1990s. These structures used high-slag-cement-content concrete that was found to be very durable (Geisler and Lang 1994). ACI 357.2R states that typical marine concretes have relatively high cement contents and many contain supplementary cementitious materials, including slag cement.

### 8.12—Mass concrete

In mass concrete, slag cement can replace large amounts of normal Type I or Type II portland cement, thereby reducing the amount of heat generated while employing commonly available materials (Neeley et al. 2004). This can eliminate the need for ASTM C150/C150M Type II moderate heat or Type IV cement. For large mass-concrete structures, replacement amounts in the 50 to 75 percent range are common (Luther et al. 2009). Although all ASTM C989/C989M grades have demonstrated success in this application—with the U.S. Army Corps of Engineers known to specify Grade 80 (Neeley et al. 2004)—in the United States, Grades 100 and 120 dominate because they are more readily available. The U.S. Army Corps of Engineers has also used slag cement in ternary and quaternary mixtures. For these, the slag cement contents ranged up to 60 percent and the slag plus Class F fly ash amount ranged from 67 to 82 percent of the total cementitious materials (Neeley et al. 2004).

Binary cementitious slag use in mass concrete is common worldwide. For example, Osborne (1998) reported that a 4600 yd<sup>3</sup> (3500 m<sup>3</sup>) placement using 70 percent slag cement showed relatively low heat generation and no thermal cracking. The 1.24 mi (1990 m) span Akashi Kaikyo bridge used ternary tremie-placed mass concrete (Kashima et al. 1992a), and inner-core, wall, and foundation mixtures employed blended cements with cementitious slag contents of approximately 50 percent and fly ash contents of approximately 30 percent (Kashima et al. 1992b).

### 8.13—Mine backfill

High slag-cement volumes have been successfully used for paste fill, or for cemented paste backfill, in underground mining backfill operations. Paste backfill is a high-density engineered material with more than 70 percent solids. The composition of paste backfill is primarily mine tailings mixed with hydraulic binders (typically portland cement with supplementary cementitious materials [SCMs]) and water. Binder dosage rates to achieve typical strength requirements in paste backfill range between 2 percent and 6 percent by mass of the mixture. Hassani and Archibald (1998) present a general overview on the early research work examining the use of slag cement in paste backfill. Binders presently used in existing mines include up to 90 percent slag. An example is Kidd Mine in Northern Ontario, Canada, which operates a 400 ton/h (362 tonnes/h) paste fill plant, where the binder is 90 percent slag cement and 10 percent portland cement where the high mine temperature accelerates the slag hydration (Ramlochan et al. 2004a; Aldea et al. 2011).

### 8.14—Pavements and bridges

In the United States and other countries where cementitious slag is commonly available, transportation structures commonly include slag cement. In the United States, the maximum amount for a specific concrete application tends to vary with the agency. Generally, once slag cement has become available in an area, agencies such as a state department of transportation specify slag-cement use in concrete and install maximum replacement limits. By 2011, most state transportation departments allowed slag cement use, some including its use with ternary mixtures (Missouri Department of Transportation 2011; Ozyildirim 2009). Research has identified combinations of portland cement with slag cement as achieving high strength and low permeability—factors associated with enhanced durability (Ozyildirim 1994; Ozyildirim and Gomez 1996).

At the U.S. Federal level, slag cement has been included in the Federal Aviation Administration's P-501 airport pavement specification (Federal Aviation Administration 2014) and the Corps of Engineers Guide specification (USACE 2014) for several decades. The use of slag cements in pavements and overlays is discussed in ACI 325.11R, 325.12R, and 325.13R.

### 8.15—Roller-compacted concrete

Slag cement, often supplied as part of a blended cement, has been used in roller-compacted concrete (RCC) in dams and pavements. In the U.S., RCC use is increasing (Pittman and Anderton 2009) and slag cement can be included as one of the cementitious ingredients.

RCC is a very dry, zero-slump mixture using aggregates not larger than 5/8 or 3/4 in., nominally. Similar to soil stabilization, RCC is proportioned to an optimum moisture content, using enough cement to yield an appropriate compressive strength (usually from 3000 to 6000 psi [20 to 40 MPa]). Optimum moisture and maximum dry density is normally determined using a modified proctor (ASTM D1557), and compressive strength cylinders are molded using a vibratory hammer (ASTM C1435/C1435M). A 500 lb/yd<sup>3</sup> (270 kg/m<sup>3</sup>) cementitious content is common, and slag cement can replace a portion of the portland cement. The optimum replacement amount can be determined via testing, and can be used in similar proportions to conventional concrete paving (25 to 50 percent replacement of cement) or higher volumes for RCC dams (50 to 80 percent). ACI 327R, ACI 207.5R, and ACI 207.1R provide additional details about design and construction of RCC pavements and dams, and the incorporation of slag cement in these products.

### 8.16—Soil stabilization

Soils have been stabilized with slag cement and with combinations of slag cement and other materials, such as portland cement (Higgins et al. 1998; Higgins and Kennedy 1999; George 2001; Kukko 2000). Unless the cementitious materials are delivered as a one-pass operation, two-pass spreading individual components may be used before mixing.

As with portland-cement soil stabilization, it is common to first determine the moisture content of the soil, measured as

an addition to the dry soil, which is associated with maximum density (usually measured by standard proctor [ASTM D698]). Portland and slag cement are then proportioned to achieve a specific compressive strength. Substituting slag for portland cement may reduce early strengths, but provide greater long-term strengths. These qualities can reduce the potential for reflective cracking in pavements, as well as provide greater long-term durability and moisture penetration resistance. When slag cement is used for soil stabilization, it is normally proportioned between 25 to 100 percent of the cementitious content (Slag Cement Association 2013). Also, wet soils with high organic or residual chemical contents that can impede portland cement hydration reactions can sometimes be stabilized more effectively with slag cement.

Slag cement, in combination with lime, has been found to mitigate the expansion and heaving associated with sulfate soils that is often present when lime is used alone (Harris et al. 2004).

Proprietary cementitious materials that are more finely ground than normal portland cement (or even Type III portland cement) and that contain slag cement, sometimes in combination with other finely milled (typically) recycled materials, have been used to stabilize soil. These often show more rapid development of properties than conventional cementitious materials. ACI 230.1R provides further guidance on the design and use of soil cement, including the use of slag cement.

### 8.17—Tilt-up

Slag cement has been used in tilt-up concrete. The concrete surface smoothness, whiter color, deeper colors (for colored concrete), and greater bond strength for exposed aggregate areas are considered advantages. Because early-age strength is usually the limiting factor, the slag-cement replacement may be lower than in other applications. Use of lower  $w/cm$  can be used to increase early-age strength. ACI 551.1R references the use of slag cement.

### 8.18—Waste stabilization

Special uses of slag cement in grouts for stabilization and solidification of waste materials were reported by Langton (1989). Research has also indicated that heavy metals can be stabilized with activated slag cements, which display continued strength and properties development in contact with materials (such as zinc) that inhibit portland cement hydration (Małolepszy and Deja 1995; Shi and Day 1996; Shi et al. 2006). Since the early 1980s, slag cement has been used in concrete to stabilize nuclear and hazardous waste, with the longest-standing such use being at the U.S. Government Savannah River nuclear facility. The low permeability and enhanced chemical resistance of relatively high-replacement slag-cement concrete can provide desired isolation from the environment. (Langton 1989; Langton et al. 2009).

### 8.19—Miscellaneous

Among many other applications of slag cement in concrete, mortar, and grout are autoclave aerated concrete, cellular concrete, pervious concrete, shotcrete and gunite, and self-consolidating concrete (SCC).

## CHAPTER 9—SUSTAINABLE DEVELOPMENT

### 9.1—Slag cement and sustainability

The use of slag cement contributes to making concrete a more sustainable material. Slag cement is an industrial by-product that originates during production of iron in a blast furnace. Through granulation and grinding, slag cement captures and makes available the materials and energy that would otherwise be wasted if slag were disposed. Slag cement is therefore regarded as a recovered industrial material, and its use makes concrete a more sustainable product because it:

- a) Reduces disposal and increases use of a recovered industrial material
- b) Reduces embodied energy
- c) Reduces embodied greenhouse gas emissions
- d) Reduces virgin material used in the manufacture of concrete
- e) Reduces cementitious material required to achieve a specified strength
- f) Improves service life through greater concrete durability
- g) Increases concrete reflectance, lowering the urban heat island effect

### 9.2—High volume slag cement use in concrete

One of the benefits of slag cement, from a sustainable perspective, is that the replacement of large proportions of portland cement with slag cement in concrete is a commonly accepted industry practice. Because portland cement is the largest contributor in concrete to embodied greenhouse gases and energy, higher substitution levels can significantly reduce these components in concrete.

Typical mixture designs for structural or paving concrete contain between 25 and 50 percent slag cement as a portion of cementitious material. At these levels, no unusual mixture designs, extensive trial batching, high levels of chemical admixtures, or increases in total cementitious material content are necessary. High-performance and mass concrete applications can use substitution rates up to 80 percent. As the slag cement percentage increases, however, consideration should be given to the effect on plastic and hardened properties (refer to Chapters 7 and 8).

### 9.3—Life-cycle inventory for slag-cement concrete

To manufacture a product such as concrete, energy and materials are used and emissions (solid, liquid, and gas) are produced. The concrete production facility (such as a ready mixed or precast plant) as well as the processes involved in production of each of concrete's constituent materials (cements, aggregates, water, and admixtures) make up the sum of embodied energy, emissions, and materials in concrete. A life-cycle inventory (LCI) is a formal process defined by ISO 14040, which documents all the inputs and outputs associated with manufacturing a product.

LCI studies on portland-cement and slag-cement concrete mixtures, performed in accordance with ISO 14040, have quantified the effects of substituting various percentages of slag cement for portland cement in a variety of appli-

**Table 9.3—Potential energy, emissions, and raw materials savings for various concrete mixtures using slag cement**

Application*	Percent slag cement	Life cycle inventory savings					
		Energy		Emissions		Materials	
		Mbtu/yd <sup>3</sup>	Percent	lb/yd <sup>3</sup>	Percent	lb/yd <sup>3</sup>	Percent
3000 psi (20.7 MPa) ready mixed concrete	35	0.26	21	116	30	197	5
	50	0.37	30	165	43	281	7
5000 psi (34.5 MPa) ready mixed concrete	35	0.39	23	173	31	296	7
	50	0.56	34	248	45	425	10
Concrete block	35	0.24	20	107	29	183	4
	50	0.34	29	154	42	263	6
Precast concrete	35	0.59	26	262	32	449	10
	50	0.84	37	374	46	640	15
High performance precast concrete	35	0.52	25	231	32	393	9
	50	0.74	36	330	46	564	13
Concrete paving	35	0.40	24	178	31	366	9
	50	0.58	35	255	45	519	12
Mass concrete	65	0.38	28	168	40	340	8
	80	0.57	42	251	59	513	13

\*Values and percentages compare 100 percent portland to portland/slag mixtures, except mass concrete, which compares 65/35 percent portland/slag cement to 35/65 percent and 20/80 percent portland/slag cement mixtures.

Note: 1 MBtu = 806.7 GJ; 1 lb/yd<sup>3</sup> = 0.765 kg/m<sup>3</sup>.

cations (Nisbet et al. 2002; Prusinski et al. 2004; Marceau and VanGeem 2008). Of specific interest are the impacts on embodied carbon dioxide (greenhouse gas), energy, and raw material use. Table 9.3 shows, for several concrete applications, the reductions achievable with various percentage substitutions of slag cement for portland cement. In the examples shown, slag cement substitution at commonly accepted levels can reduce embodied energy, carbon dioxide, and raw material use in concrete by up to 52, 59, and 15 percent, respectively.

#### 9.4—Reflectance

Slag cement powder is lighter in color than gray portland cement, fly ash, or silica fume (Fig. 9.4). As a result, concrete manufactured with slag cement cures to a lighter color and is more reflective than concrete made with the other cementitious materials, except for white portland cement (Marceau et al. 2007). Concrete is generally considered a light building material, whatever its constituents; however, the lighter color and higher reflectance of slag cement concrete can provide additional benefits:

a) Lighter-colored pavements, such as streets, highways, and parking lots, produce brighter environments with higher visibility and improved safety.

b) Lighting requirements may be reduced with more reflective pavements, floors, or walls.

c) More reflective pavements and structures help reduce temperatures in cities (the urban heat island effect), which lowers the energy needed for cooling, and lowers ozone levels.

Marceau et al. (2007) measured solar reflectance, in accordance with ASTM C1549, on 45 concrete mixtures with a

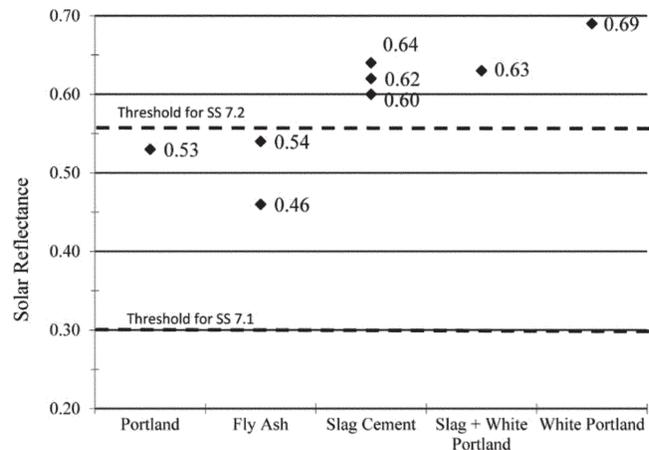


Fig. 9.4—Reflectance of concretes produced with identical aggregates and portland cements (adapted from Marceau et al. [2007]).

variety of different gray and white portland cements, fly ashes (Class C and F), slag cements, and coarse and fine aggregates. Their study found that the supplementary cementitious materials (SCMs) had the second greatest effect on solar reflectance next to portland cement. Figure 9.4 shows a subset of the 45 mixtures, concretes made with identical gray portland cements and aggregates, with different fly ashes and slag cements. Solar reflectance is important in determining LEED points (9.7) for urban heat island. Figure 9.4 indicates that only one slag cement-gray portland cement and one white cement mixture, with the given aggregates,

**Table 9.7—Potential LEED-NC points with slag cement**

Category	Credit	LEED Version	Description	Possible points	Potential slag cement contribution
Sustainable sites	SS 3	2.1 and 2.2	Brownfield Redevelopment	1	Slag cement can be used to help accomplish in-place stabilization and solidification of contaminated soils at brownfield sites.
Sustainable sites	SS 7.1	2.1 and 2.2	Heat island effect: nonroof	1	Slag cement is a light-colored material, making concrete whiter with higher albedo compared with other cementitious materials.
Materials and resources	MR 1.1 and MR 1.2	2.1	Maintain 75 and 100 percent of existing walls, floors, and roof	2	Slag cement can extend a structure's useful service life (if it was used in the original concrete) because it improves concrete durability in areas such as corrosion resistance, sulfate attack and alkali-aggregate reaction.,
		2.2	Maintain 75 and 95 percent of existing walls, floors, and roof	2	
Materials and resources	MR 4.1 and MR 4.2	2.1	Recycled content: 5 and 10 percent of (post-consumer and 1/2 post-industrial)	2	Slag cement is a recovered post-industrial material; therefore, its use contributes to the total recycled content of a structure.
		2.2	10 and 20 percent of (post-consumer and 1/2 of pre-consumer)	2	
Materials and resources	MR 5.1	2.1	Regional materials: 20 percent manufactured regionally	1	Most slag cement in the U.S. is recovered at iron blast furnaces located within the U.S. or nearby in Canada. The slag cement supplier can provide point of origin so the 500-mile radius requirement can be calculated for a specific project. SCA also has facility maps available.
Materials and resources	MR 5.2	2.2	Regional materials: 50 percent extracted regionally	1	
Materials and resources	MR 5.1 and MR 5.2	2.2	Regional materials: 10 and 20 percent extracted, processed, and manufactured regionally	2	
Innovation in design	ID 1.1	2.1 and 2.2	Credit interpretation ruling IDc11, reduction of total portland cement content for cast-in-place concrete	1	This credit is meant to reduce embodied greenhouse gas emissions in concrete. Slag cement can replace significant amounts of portland cement, and may reduce total cementitious material needed.
Innovation in design	ID 1.2	2.2	Exemplary performance	2	Additional points can be obtained by exceeding the requirements of MR Credits 4 and 5. If a project demonstrates 30 percent or greater total recycled value an additional point can be earned. Another point could be earned if a project demonstrates 40 percent or greater for regionally extracted, harvested, and manufactured materials.

were able to achieve the higher level of LEED-NC reflectivity value of 0.64.

### 9.5—Federally-funded projects

The **U.S. Environmental Protection Agency (1996)** recognized slag cement as a recovered product under the federal Resource Conservation Recovery Act. This classification requires that slag cement be allowed in concrete on federally-funded projects (greater than \$10,000 in cost), unless there is a documentable technical or market reason for it not being specified. These requirements are detailed in EPA's "Comprehensive Procurement Guidelines" (**U.S. Environmental Protection Agency 1994**).

### 9.6—Service life

Slag cement is a material that contributes to increasing the service life of concrete structures. Analytical tools can help designers quantify the extension to service life by adding slag cement (and other durability-enhancing strategies) to their designs. Slag cement, as documented in previous chapters, results in concrete with:

- a) Lower permeability

- b) Increased corrosion resistance
- c) Improved resistance to sulfate attack and alkali-silica reactivity (ASR)
- d) Reduced thermal stress and cracking

### 9.7—Green building rating systems

Many green building rating systems have been developed worldwide to provide quantitative measures that determine whether a building is green. In the United States, the most predominant system is the U.S. Green Building Council's LEED system. LEED-NC is the standard that is used for new construction and major rehabilitation of commercial and industrial buildings. Table 9.7 summarizes the LEED-NC points to which slag cement can contribute.

## CHAPTER 10—REFERENCES

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

ACI 207.5R-11—Report on Roller-Compacted Mass Concrete

ACI 211.1-91(09)—Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete

ACI 212.3R-10—Report on Chemical Admixtures for Concrete

ACI 229R-13—Report on Controlled Low-Strength Materials

ACI 230.1R-09—Report on Soil Cement

ACI 234R-06(12)—Guide for the Use of Silica Fume in Concrete

ACI 301-16—Specifications for Structural Concrete

ACI 308R-01(08)—Guide to Curing Concrete

ACI 318-14—Building Code Requirements for Structural Concrete and Commentary

ACI 325.11R-01—Accelerated Techniques for Concrete Paving

ACI 325.12R-02(13)—Guide for Design of Jointed Concrete Pavements for Streets and Local Roads

ACI 325.13R-06—Concrete Overlays for Pavement Rehabilitation

ACI 327R-14—Guide to Roller Compacted Concrete Pavements

ACI 357.2R-10—Report on Floating and Float-in Concrete Structures

ACI 551.1R-14—Guide to Tilt-Up Concrete Construction

#### *ASTM International*

ASTM C94/C94M-15—Standard Specification for Ready-Mixed Concrete

ASTM C150/C150M-15—Standard Specification for Portland Cement

ASTM C186-15—Standard Test Method for Heat of Hydration of Hydraulic Cement

ASTM C227-10—Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)

ASTM C270-14—Standard Specification for Mortar for Unit Masonry

ASTM C403/C403M-08—Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance

ASTM C476-10—Standard Specification for Grout for Masonry

ASTM C595/C595M-15—Standard Specification for Blended Hydraulic Cements

ASTM C666/C666M-15—Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

ASTM C672/C672M-12—Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals

ASTM C989/C989M-14—Standard Specification for Slag Cement for Use in Concrete and Mortars

ASTM C1012/C1012M-15—Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution

ASTM C1157/C1157M-11—Standard Performance Specification for Hydraulic Cement

ASTM C1260-14—Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)

ASTM C1293-08(2015)—Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silicate Reaction

ASTM C1435/C1435M-14—Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer

ASTM D698-12—Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft<sup>3</sup> (600 kN-m/m<sup>3</sup>))

ASTM C1549-09(2014)—Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer

ASTM D1557-12—Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft<sup>3</sup> (2,700 kN-m/m<sup>3</sup>))

#### *CSA Group*

CSA A3001-13—Cementitious Materials for Use in Concrete

#### *International Organization for Standardization*

ISO 14040:2006—Environmental Management—Life Cycle Assessment—Principles and Framework

#### **Authored documents**

Afrani, I., and Rogers, C., 1994, “The Effects of Different Cementing Materials and Curing on Concrete Scaling,” *Cement, Concrete and Aggregates*, V. 16, No. 2, pp. 132-139. doi: [10.1520/CCA10291J](https://doi.org/10.1520/CCA10291J)

Aitcin, P.-C., and Neville, A., 1993, “High-Performance Concrete Demystified,” *Concrete International*, V. 15, No. 1, Jan., pp. 21-26.

Aldea, C. M.; Cornelius, B. J.; and McGuinness, M., 2011, “Kidd Mine Paste Fill Binder Research Study,” *Proceedings of the 14th International Seminar on Paste and Thickened Tailings*, R. J. Jewells and A. B. Fourie, eds., Australian Center for Geomechanics, Perth, Australia, pp. 505-516.

Bakker, R. F. M., 1980, “On the Cause of Increased Resistance of Concrete Made from Blast-Furnace Cement to Alkali Reaction and to Sulfate Corrosion,” PhD thesis, RWTH-Aachen, 118 pp.

Bakker, R. F. M., 1983, “Permeability of Blended Cement Concrete,” *Fly Ash, Silica Fume, Slag, and Other Mineral By-Products in Concrete*, SP-79, V. 1, American Concrete Institute, Farmington Hills, MI, pp. 589-605.

Bamforth, P. B., 1980, “In Situ Measurement of the Effect of Partial Portland Cement Replacement Using Either Fly Ash or Ground Granulated Blast-Furnace Slag on the Performance of Mass Concrete,” *Proceedings - Institution of Civil Engineers*, V. 69, No. 3, pp. 777-800. doi: [10.1680/iicep.1980.2377](https://doi.org/10.1680/iicep.1980.2377)

Barnett, S. J.; Soutsos, M. N.; Bungey, J. H.; and Millard, S. G., 2007, “Fast Track Construction with Slag Cement Concrete: Adiabatic Strength Development and Strength Prediction,” *ACI Materials Journal*, V. 104, No. 4, July-Aug., pp. 388-396.

Bickley, J. A.; Ryell, J.; Rogers, C.; and Hooton, R. D., 1991, “Some Characteristics of High Strength Structural

Concrete,” *Canadian Journal of Civil Engineering*, V. 18, No. 5, pp. 885-889. doi: [10.1139/91-107](https://doi.org/10.1139/91-107)

Bickley, J. A.; Ryell, J.; Rogers, C.; and Hooton, R. D., 1994, “Some Characteristics of High Strength Structural Concrete: Part 2,” *Canadian Journal of Civil Engineering*, V. 21, No. 6, pp. 1084-1087. doi: [10.1139/94-113](https://doi.org/10.1139/94-113)

Bijen, J., 1996, “Blast Furnace Slag Cement for Durable Marine Structures,” Association of the Netherlands Cement Industry, BetonPrisima, ‘s-Hertogenbosch, the Netherlands, 62 pp.

Bleszynski, R.; Hooton, R. D.; Thomas, M. D. A.; and Rogers, C. A., 2002, “Durability of Ternary Blend Concrete with Silica Fume and Blast-Furnace Slag: Laboratory and Outdoor Exposure Site Studies,” *ACI Materials Journal*, V. 99, No. 5, Sept.-Oct., pp. 499-508.

Bleszynski, R. F.; Thomas, M. D. A.; and Hooton, R. D., 2000, “Use of Ternary Blended Cements to Control ASR,” *Proceedings of the 11th International Conference on Alkali-Aggregate Reaction in Concrete*, M. A. Berube, B. Fournier, and B. Durand, eds., CRIB, Quebec City, ON, Canada, pp. 583-592.

Bouzoubaa, N.; Bilodeau, A.; Fournier, B.; Hooton, R. D.; Gagne', R.; and Jolin, M., 2008, “Deicing Salt Scaling Resistance of Concrete Incorporating Supplementary Cementing Materials: Laboratory and Field Test Data,” *Canadian Journal of Civil Engineering*, V. 35, No. 11, pp. 1261-1275. doi: [10.1139/L08-067](https://doi.org/10.1139/L08-067)

Bouzoubaa, N., and Foo, S., 2005, “Use of Fly Ash and Slag in Concrete: A Best Practice Guide,” *Materials and Technology Laboratory*, MTL 2004-16 (TR-R), Minerals and Metals Program of the Government of Canada Action Plan 2000 on Climate Change, 40 pp.

Boyd, A. J., and Hooton, R. D., 2007, “Long-Term Scaling Performance of Concretes Containing Supplementary Cementing Materials,” *Journal of Materials in Civil Engineering*, V. 19, No. 10, Oct., pp. 820-825. doi: [10.1061/\(ASCE\)0899-1561\(2007\)19:10\(820\)](https://doi.org/10.1061/(ASCE)0899-1561(2007)19:10(820))

Brooks, J. J.; Wainwright, P. J.; and Boukendakji, M., 1992, “Influence of Slag Type and Replacement Level on Strength, Elasticity, Shrinkage, and Creep of Concrete,” *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, Proceedings of the Fourth International Conference, SP-132, American Concrete Institute, Farmington Hills, MI, V. 2, pp. 1325-1341.

Chojnacki, B., 1981, “Sulfate Resistance of Blended (Slag) Cement,” *Report No. EM-52*, Ministry of Transportation and Communications, Downsview, ON, Canada.

Cook, D. J.; Hinczak, I.; and Duggan, R., 1986, “Volume Changes in Portland-Blast Furnace Slag Cement Concrete,” *Second International Conference on Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, V. 2, Supplementary Papers, Madrid, Spain.

Cornielle, A., 1988, “Alkali-Aggregate Reaction in French Dams,” *Ecole Nationale des Ponts et Chaussées—Session Durabilité des Structures en Béton*, Mar., 14 pp. (in French)

Cotsworth, R. P., 1981, “National Slag’s Pelletizing Process,” *Symposium on Slag Cement*, University of Alabama, Birmingham, AL.

Cox, H. P.; Coleman, R. B.; and White, L., 1950, “Effect of Blast-Furnace-Slag Cement on Alkali-Aggregate Reaction in Concrete,” *Pit and Quarry*, V. 45, No. 5, pp. 95-96.

Dunker, K. F., 2003, “HPC for I-235 Bridge Reconstruction in Iowa,” *HPC Bridge Views*, Issue 29, Sept./Oct., pg. 1. *Engineering News Record*, 1991, “Society Tower, Concrete Today,” May 6, pg. C-72.

Federal Aviation Administration, 2014, “Specification Part VI for Rigid Pavement, Item P-501 for Portland Cement Concrete Pavement (AC 150/5370-10G),” Federal Aviation Administration, Washington, DC, pp. 291-337.

Forss, B., 1982, “F-Cement, a Low-Porosity Slag Cement for the Precast Industry,” *International Conference on Slag and Blended Cements*, University of Alabama, Birmingham, AL, 12 pp.

Fulton, F. S., 1974, “The Properties of Portland Cement Containing Milled Granulated Blast-Furnace Slag,” *Monograph*, Portland Cement Institute, Johannesburg, South Africa, pp. 4-46.

Geisler, J., and Lang, E., 1994, “Long-Term Durability of Non-Air-Entrained Concrete Structures Exposed to Marine Environments and Freezing-and-Thawing Cycles,” *Third CANMET/ACI International Conference on Durability of Concrete*, Supplementary Papers, Nice, France, 1994, pp. 715-737.

George, K. P., 2001, “Soil Stabilization Field Trial,” PhD thesis, Department of Civil Engineering, University of Mississippi, Oxford, MS, 118 pp.

Ghorab, H. Y.; Heinz, D.; Ludwig, U.; Meskendahl, T.; and Wolter, A., 1980, “On the Stability of Calcium Aluminate Sulphate Hydrates in Pure Systems and in Cements,” *Proceedings of the 7th International Congress on the Chemistry of Cement*, V. 4, Septima, Paris, pp. 496-503.

Glukhovskiy, V. D.; Rostovskaya, G. S.; and Rumyna, G. V., 1980, “High Strength Slag Alkaline Cements,” *7th International Congress on the Chemistry of Cement*, Septima, Paris, pp. 164-168.

Harris, J.; Sebasta, S.; and Scullion, T., 2004, “Hydrated Lime Stabilization of Sulfate-Bearing Vertisols in Texas,” *Transportation Research Record No. 1868*, Transportation Research Board, Washington DC, pp. 31-39.

Hassani, F., and Archibald, J., 1998, eds., *Mine Backfill*, CIM, AA Balkema, Rotterdam.

Heijnen, W. M. M., 1992, “Alkali-Aggregate Reactions in the Netherlands,” *Proceedings of the 9th International Conference on Alkali-Aggregate Reaction in Concrete*, London, UK, pp. 432-439.

Heijnen, W. M. M.; Larbi, J. A.; and Siemes, A. J. M., 1996, “Alkali-Silica Reaction in the Netherlands,” *Proceedings of the 10th International Conference on Alkali-Aggregate Reaction in Concrete*, Melbourne, Australia, pp. 109-116.

Higgins, D. D., 2003, “Increased Sulfate Resistance of GGBS Concrete in the Presence of Carbonate,” *Cement and Concrete Composites*, V. 25, No. 8, pp. 913-919. doi: [10.1016/S0958-9465\(03\)00148-3](https://doi.org/10.1016/S0958-9465(03)00148-3)

Higgins, D. D., and Kennedy, J., 1999, “Lime + Ground Granulated Blast Furnace Slag Stabilisation of Boulder Clay on the ‘A421’ Tingewick Bypass,” *3rd European Symposium*

on the Performance and Durability of Bituminous Materials and Hydraulic Stabilised Composites, Leeds, UK, 15 pp.

Higgins, D. D.; Kinuthia, J. M.; and Wild, S., 1998, "Soil Stabilization Using Lime-Activated Ground Granulated Blast Furnace Slag," *Proceedings of the Sixth CANMET/ACI International Conference*, SP-178, American Concrete Institute, Farmington Hills, MI, pp. 1057-1074.

Hogan, F. J., and Meusel, J. W., 1981, "Evaluation for Durability and Strength Development of a Ground Granulated Blast-Furnace Slag," *Cement, Concrete and Aggregates*, V. 3, No. 1, pp. 40-52. doi: [10.1520/CCA10201J](https://doi.org/10.1520/CCA10201J)

Holcim (US) Inc., 2002, "GranCem Cement," Dundee, MI, 16 pp.

Hooton, R. D., 2000, "Canadian Use of Ground Granulated Blast-Furnace Slag as a Supplementary Cementing Material for Enhanced Performance of Concrete," *Canadian Journal of Civil Engineering*, V. 27, No. 4, pp. 754-760. doi: [10.1139/100-014](https://doi.org/10.1139/100-014)

Hooton, R. D., and Emery, J. J., 1980, "Pelletized Slag Cement: Autoclave Reactivity," *Proceedings of the 7th International Congress on the Chemistry of Cement*, Septima, Paris, pp. 43-47.

Hooton, R. D., and Emery, J. J., 1990, "Sulfate Resistance of a Canadian Slag," *ACI Materials Journal*, V. 87, No. 6, Nov.-Dec., pp. 547-555.

Hooton, R. D.; Rogers, C. A.; MacDonald, C. A.; and Ramlochan, T., 2013, "20-Year Field Evaluation of Alkali-Silica Reaction Mitigation," *ACI Materials Journal*, V. 110, No. 5, Sept.-Oct., pp. 539-548.

Hooton, R. D.; Stanish, K.; Angel, J. P.; and Prusinski, J., 2009, "The Effect of Ground Granulated Blast Furnace Slag (Slag Cement) on the Drying Shrinkage of Concrete—A Critical Review of the Literature," *Slag Cement Concrete*, SP-263, American Concrete Institute, Farmington Hills, MI, pp. 91-108.

Hooton, R. D.; Thomas, M. D. A.; Ramlochan, T.; and Bleszynski, R. F., 2008, "Durability of Ternary Blend Concrete with Silica Fume and Blast-Furnace Slag Laboratory and Outdoor Exposure Site Studies," *Proceedings of the 8th International Conference on Alkali-Aggregate Reactions*, Trondheim, Norway.

Kashima, S.; Furuya, N.; and Yamaoka, Y., 1992a, "High-Strength Concrete for Wall Foundation Using Ternary Blended Cement with Intermixture of Blast-Furnace Slag and Fly Ash," *Proceedings of the Fourth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-132, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1451-1469.

Kashima, S.; Sakamoto, M.; Okada, S.; Iho, T.; and Nakagawa, Y., 1992b, "Application of High Slag and Fly Ash, Low-Heat Cement to Antiwashout Underwater Concrete," *Proceedings of the Fourth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-132, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1601-1619.

Klieger, P., and Isberner, A. W., 1967, "Laboratory Studies of Blended Cement—Portland Blast-Furnace Slag Cements," *Journal of the PCA Research and Development Department Laboratories*, V. 9, No. 3, Sept., pp. 2-22.

Kukko, H., 2000, "Stabilization of Clay with Inorganic By-Products," *Journal of Materials in Civil Engineering*, V. 12, No. 4, Nov., pp. 307-309. doi: [10.1061/\(ASCE\)0899-1561\(2000\)12:4\(307\)](https://doi.org/10.1061/(ASCE)0899-1561(2000)12:4(307))

Lang, E., and Geisler, J. F., 1996, "Use of Blast Furnace Slag Cement with High Slag Content for High-Performance Concrete," *Concrete in the Service of Mankind—Radical Concrete Technology*, R. K. Dhir and P. C. Hewlett, eds., E&FN Spon, pp. 67-76.

Langton, C. A., 1989, "Slag Based Materials for Toxic Based Metal and Radioactive Waste Stabilization," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, Proceedings of the Third Annual Conference, SP-114, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, V. 2, pp. 1697-1706.

Langton, C. A.; Kosson, D. S.; Garrabrants, A. C.; and Brown, K. G., 2009, "Reference Cases for Use in the Cementitious Barriers Partnership—Project 9446," Savannah River National Laboratory Report SRNL-STI-2009-00005, Proceedings, WM 2009, Phoenix, AZ, 12 pp. <http://sti.srs.gov/fulltext/SRNL-STI-2010-00712.pdf>

Lankard, D., 1992, "Evaluation of Concretes for Bridge Deck Applications," *Report No. I-2930-1 to Ohio Department of Transportation*, Lankard Materials Laboratory, Inc. Columbus, OH, 29 pp.

Lea, F. M., 1971, *The Chemistry of Cement and Concrete*, third edition, Chemical Publishing Co., New York, pp. 454-489.

Lewis, D. W., 1981, "History of Slag Cements," *Symposium on Slag Cement*, University of Alabama, Birmingham, AL.

Lewis, M. C., 1996, "Heat Curing and Delayed Ettringite Formation in Concretes," PhD thesis, University of London (Imperial College), London, UK.

Luther, M. D.; Bohme, P.; and Wilson, W., 2009, "Case Studies—North American Mass-Concrete Projects Featuring ASTM C989 Slag Cement," *Slag Cement Concrete*, SP-263, C.-M. Aldea, ed., American Concrete Institute, Farmington Hills, MI, pp. 13-30.

Luther, M. D., and Mikols, W. J., 1993, "Effect of Ground Granulated Blast-Furnace Slag Fineness on High-Strength Concrete Properties," *Proceedings of the Utilization of High-Strength Concrete Symposium*, V. 2, Lillehammer, Norway, pp. 822-829.

Luther, M. D.; Mikols, W. J.; DeMaio, A. J.; and Whitlinger, J. E., 1994, "Scaling Resistance of Ground Granulated Blast Furnace Slag (GGBFS) Concretes," *Durability of Concrete*, Proceedings of the Third International Conference, SP-145, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 47-64.

Malhotra, V. M., 1980, "Strength and Durability Characteristics of Concrete Incorporating a Pelletized Blast Furnace Slag," *Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete*, SP-79, V. M. Malhotra,

ed., American Concrete Institute, Farmington Hills, MI, pp. 891-922.

Malolepszy, J., and Deja, J., 1995, "Effect of Heavy Metals Immobilization on the Properties of Alkali Activated Slag Mortars," *Proceedings of the Fifth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-153, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1087-1102.

Marceau, M. L.; Nisbet, M. A.; and VanGeem, M. G., 2007, "Life Cycle Inventory of Portland Cement Concrete," PCA R&D Serial No. 3007, Portland Cement Association, Skokie, IL, 113 pp.

Marceau, M. L., and VanGeem, M. G., 2008, "Solar Reflectance Values for Concrete," *Concrete International*, V. 30, No. 8, Aug., pp. 52-58.

Marushima, N.; Kuroha, K.; Tomatsuri, T.; Koibuchi, K.; and Ishikawa, Y., 1993, "Study on High Strength Concrete with Blast Furnace Slag Cement Incorporating Very Fine Slag," *Proceedings of the Utilization of High-Strength Concrete*, Lillehammer, V. 2, I. Holand and E. Sellevold, eds., Norwegian Concrete Association, Oslo, Norway, pp. 830-837.

Mary, M., 1951, "Preparation du Ciment du Latier par Voie Humide le Proces Trief et Son Application au Barrage de Bort-les-orgues," *Annales de l'institute technique du Bati-ment et des travaux publiques*, No. 200, July-Aug.

Mather, B., 1957, "Laboratory Tests of Portland Blast-Furnace Slag Cements," *ACI Journal Proceedings*, V. 54, No. 3, Sept., pp. 205-232.

Mehta, P. K., 1980, "Durability of Concrete in Marine Environment—A Review," *Performance of Concrete in Marine Environment*, SP-65, American Concrete Institute, Farmington Hills, MI, pp. 1-20.

Meusel, J. W., and Rose, J. H., 1983, "Production of Granulated Blast Furnace Slag at Sparrows Point, and the Workability and Strength Potential of Concrete Incorporating the Slag," *Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete*, SP-79, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, V. 1, pp. 867-890.

Mid-Atlantic Regional Technical Committee, 1993, "Guide to Alkali-Aggregate Reactivity," NRMCA, Silver Spring, MD, 17 pp.

Missouri Department of Transportation, 2011, "Missouri Standard Specification Book for Highway Construction," Sections 501.14 and 501.14.2, Jefferson City, MO, Oct.

Nagataki, S., 1996, "High-Strength Concrete in Japan: History and Progress," *High-Strength Concrete: An International Perspective*, SP-167, J. A. Bickley, ed., American Concrete Institute, Farmington Hills, MI, pp. 7-16.

Neeley, B. D.; Bombich, A. A.; and Green, B. H., 2004, "Use of Multiple Cementitious Materials in Concrete Mixtures at Corps of Engineers Projects," *George C. Hoff Symposium on High-Performance Concrete and Concrete for Marine Environment*, T. C. Liu, ed., pp. 73-91.

Nisbet, M. A.; Marceau, M. L.; and VanGeem, M. G., 2002, "Environmental Life Cycle Inventory of Portland Cement Concrete," *Report SN2137a*, Portland Cement Association, Skokie, IL, 67 pp.

Oberholster, R. E., 1989, "Alkali-Aggregate Reaction in South Africa, Some Recent Developments in Research," *Proceedings of the 8th International Conference on Alkali-Aggregate Reaction*, Japan, pp. 77-82.

Oberholster, R. E., and Davies, G., 1987, "The Effect of Mineral Admixtures on the Alkali-Aggregate Expansion of Concrete under Outdoor Exposure Conditions," *Proceedings of the 7th International Conference on Alkali-Aggregate Reactions*, Noyes Publications, NJ, pp. 60-65.

Ogawa, S.; Yamada, K.; Hirao, H.; Hyoda, H.; Matsui, A.; and Hooton, R. D., 2009, "Sulfate Resistance Improvement of Blended Cement Based on Ground Granulated Blast Furnace Slag," *Journal of Research of the Taiheiyo Cement Corporation*, No. 156, pp. 3-11.

Ohio Department of Transportation, 1994, "Specification for High-Performance Concrete," Columbus, OH, 11 pp.

Osborne, G., and Singh, B., 1995, "The Durability of Concretes Made with Blends of High-Alumina Cement and Ground Granulated Blast Furnace Slag," *Proceedings of the Fifth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-153, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 885-909.

Osborne, G. J., 1986, "Carbonation of Blastfurnace Slag Cement Concrete," *Durability of Building Materials*, V. 4, pp. 81-96.

Osborne, G. J., 1989, "Carbonation and Permeability of Blast-Furnace Slag Cement Concretes from Field Structures," *Fly Ash, Slag and Natural Pozzolans in Concrete*, SP-114, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1209-1237.

Osborne, G. J., 1998, "Durability of Portland Blast-Furnace Slag Cement Concrete, Joe G. Cabrera Symposium on Durability of Concrete Materials," *Proceedings of the Sixth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-178, R. N. Swamy, ed., American Concrete Institute, Farmington Hills, MI, pp. 79-99.

Ozyildirim, C., 1994, "Resistance of Penetration of Chlorides into Concrete Containing Latex, Fly Ash, Slag, and Silica Fume," *Durability of Concrete*, SP-145, K. P. Chong, ed., American Concrete Institute, Farmington Hills, MI, pp. 503-518.

Ozyildirim, C., 2009, "Use of Concrete Containing Slag Cement in Transportation Structures in Virginia," *Slag Cement Concrete*, SP-263, C.-M. Aldea, ed., American Concrete Institute, Farmington Hills, MI, pp. 1-29.

Ozyildirim, C., and Gomez, J., 1996, "High-Performance Concrete in Bridge Structures in Virginia," *Proceedings of the Fourth Engineering Materials Conference*, K. P. Chong, ed., American Society of Civil Engineers, Washington, DC, pp. 1357-1366.

Pacheco-Torgal, F.; Castro-Gomes, J.; and Jalali, S., 2008a, "Alkali-Activated Binders: A Review Part 1. Historical Background, Terminology, Reaction Mechanisms and Hydration Products," *Construction & Building Materials*, V. 22, No. 7, pp. 1305-1314. doi: [10.1016/j.conbuildmat.2007.10.015](https://doi.org/10.1016/j.conbuildmat.2007.10.015)

- Pacheco-Torgal, F.; Castro-Gomes, J.; and Jalali, S., 2008b, "Alkali-Activated Binders: A Review Part 2. About Materials and Binders Manufacture," *Construction & Building Materials*, V. 22, No. 7, pp. 1315-1322. doi: [10.1016/j.conbuildmat.2007.03.019](https://doi.org/10.1016/j.conbuildmat.2007.03.019)
- Parrott, L. J., 1987, "A Review of Carbonation in Reinforced Concrete," *Building Research Establishment Report C/1-0987*.
- Pittman, D. W., and Anderton, G. L., 2009, "The Use of Roller-Compacted Concrete (RCC) Pavements in the United States," *Sixth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control (MAIREPAV6)*, Turin, Italy.
- Prusinski, J. P.; Marceau, M. L.; and VanGeem, M. G., 2004, "Life Cycle Inventory of Slag Cement Concrete," *Eighth CANMET/ACI Eighth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, SP-221, American Concrete Institute, Farmington Hills, MI, 26 pp.
- Ramlochan, T.; Grabinsky, M. W.; and Hooton, R. D., 2004a, "Microstructural and Chemical Investigations of Cemented Paste Backfills," *Proceedings of Tailings and Mine Waste '04*, Taylor & Francis Group, London, pp. 293-304.
- Ramlochan, T.; Thomas, M. D. A.; and Hooton, R. D., 2004b, "The Effect of Pozzolans and Slag on the Expansion of Mortars Cured at Elevated Temperature; Part II: Microstructural and Microchemical Investigations," *Cement and Concrete Research*, V. 34, No. 8, pp. 1341-1356. doi: [10.1016/j.cemconres.2003.12.026](https://doi.org/10.1016/j.cemconres.2003.12.026)
- Regourd, M., 1980a, "Characterization of Thermal Activation of Slag Cements," *Proceedings of the 7th International Congress on the Chemistry of Cements*, Septima, Paris, V. 2, III-3, pp. 105-111.
- Regourd, M., 1980b, "Structure and Behavior of Slag Portland Cement Hydrates," *Proceedings of the 7th International Congress on the Chemistry of Cements*, Septima, Paris, V. 1, III-2, pp. 10-18.
- Regourd, M., 1983, "Microanalytical Studies (X-Ray Photoelectron Spectrometry) of Surface Hydration Reactions of Cement Compounds," *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, V. 310, No. 1511, pp. 85-92.
- Robertson, J. L., 1982, "At Submicron Fineness, Expanded Slag Is a Cement Replacement," *Rock Products*, Apr.
- Robins, P. J., and Austin, S. A., 1995, "Fly Ash and Slag Jet-Blast Resistant Concretes," *5th International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-153, American Concrete Institute, Farmington Hills, MI, pp. 1141-1163.
- Rose, J. H., 1987, "The Effect of Cementitious Blast-Furnace Slag on Chloride Permeability of Concrete," *Corrosion, Concrete, and Chlorides*, SP-102, F. W. Gibson, ed., American Concrete Institute, Farmington Hills, MI, pp. 107-125.
- Roy, D. M., 1989, "Hydration, Microstructure and Chloride Diffusion of Slag-Cement Pastes and Mortars," *Fly Ash, Silica Fume, and Natural Pozzolans in Concrete*, SP-114, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1265-1281.
- Roy, D. M., and Idorn, G. M., 1982, "Hydration, Structure, and Properties of Blast Furnace Slag Cements, Mortars, and Concrete," *ACI Journal Proceedings*, V. 79, No. 6, Nov.-Dec., pp. 445-457.
- Roy, D. M., and Parker, K. M., 1983, "Microstructures and Properties of Granulated Slag-Portland Cement Blends at Normal and Elevated Temperatures," *Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete*, SP-79, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 397-414.
- Shi, C., and Day, R. L., 1996, "Alkali-Slag Cements for the Solidification of Radioactive Wastes, Stabilization and Solidification of Hazardous, Radioactive, and Mixed Wastes," ASTM STP-1240, T. M. Gilliam and C. C. Wiles, eds., ASTM International, West Conshohocken, PA, pp. 163-173.
- Shi, C.; Roy, D. M.; and Krivenko, P., 2006, *Alkali-Activated Cements and Concretes*, Taylor & Francis, 372 pp.
- Sivasundaram, V., and Malhotra, V. M., 1991, "Properties of Concrete Incorporating Low Quantity of Cement and High Volumes of Ground Granulated Slag," *Project 30.37.01*, Mineral Sciences Laboratories, CANMET, Ottawa, ON, Canada, May, 28 pp.
- Slag Cement Association, 2002a, "Ternary Concrete Mixtures with Slag Cement," *Slag Cement in Concrete Information Sheet Series*, No. 20, Slag Cement Association, Farmington Hills, MI, 2 pp.
- Slag Cement Association, 2002b, "Concrete Proportioning," *Slag Cement in Concrete Information Sheet Series*, No. 2, Slag Cement Association, Farmington Hills, MI, 2 pp.
- Slag Cement Association, 2009, "Concrete Proportioning Info," *Slag Cement in Concrete Information Sheet Series*, No. 2, Slag Cement Association, Farmington Hills, MI, 2 pp.
- Slag Cement Association, 2013, "Slag Cement Association 2012 Project of the Year Concrete Awards," *Concrete International*, V. 25, No. 8, Aug., pp. 35-38.
- Smolczyk, H. G., 1977, "The Use of Blast-Furnace Slag Cement in Reinforced and Prestressed Concrete," *Proceedings of the 6th International Steelmaking Day*, Paris.
- Smolczyk, H. G., 1978, "The Effect of the Chemistry of Slag on the Strength of Blast-Furnace Cements," *Zement-Kalk-Gips, Wiesbaden*, V. 31, No. 6, pp. 294-296.
- Soles, J. A.; Malhotra, V. M.; and Chen, H., 1989, "CANMET Investigations of Supplementary Cementing Materials for Reducing Alkali-Aggregate Reactions: Part I—Granulated/Pelletized Blast-Furnace Slags," *Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, SP-114, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1637-1656.
- Soutsos, M.; Hatzitheodorou, A.; Kwasny, J.; and Kanavaris, F., 2016, "Effect of In Situ Temperature on the Early Age Strength Development of Concretes with Supplementary Cementitious Materials," *Construction & Building Materials*, V. 103, pp. 105-116. doi: [10.1016/j.conbuildmat.2015.11.034](https://doi.org/10.1016/j.conbuildmat.2015.11.034)

Spence, R. D.; Bostick, W. D.; McDaniels, E. W.; Giliam, T. M.; Shoemaker, J. L.; Tallent, P. K.; Morgan, I. L.; Evans-Brown, B. S.; and Dodson, K. E., 1989, "Immobilization of Technetium in Blast Furnace Slag Grouts," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-114, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1579-1596.

Swamy, N.; Nakamura, N.; and Sakai, M., 1993, "High-Strength with Durability—The Twin Offsprings of Fine Slag Cements," *Proceedings of the Utilization of High-Strength Concrete*, I. Holand and E. Sellevold, eds., Norwegian Concrete Association, Oslo, Norway, pp. 962-969.

Talling, B., and Brandstettr, J., 1989, "Present State and Future of Alkali-Activated Slag Concrete," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-114, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1519-1545.

Tazawa, E.; Yonekura, A.; and Tanaka, S., 1989, "Drying Shrinkage and Creep of Concrete Containing Granulated Blast Furnace Slag," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-114, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1325-1343.

Thomas, A., 1979, "Metallurgical and Slag Cements, the Indispensable Energy Savers," *General Practices*, IEEE Cement Industry 21 Technical Conference, 108 pp.

Thomas, M. D. A., 1996, "Review of the Effect of Fly Ash and Slag on Alkali-Aggregate Reaction in Concrete," *Building Research Establishment Report BR 314*, Construction Research Communications Ltd., Watford, UK, 117 pp.

Thomas, M. D. A.; Hopkins, D. S.; Perreault, M.; and Cail, K., 2007, "Ternary Cement in Canada," *Concrete International*, V. 29, No. 7, July, pp. 59-64.

Thomas, M. D. A., and Innis, F. A., 1998, "Effect of Slag on Expansion Due to Alkali-Aggregate Reaction in Concrete," *ACI Materials Journal*, V. 95, No. 6, Nov.-Dec., pp. 716-724.

Thomas, M. D. A.; Scott, A.; Bremner, T. W.; Bilodeau, A.; and Day, D., 2008, "Performance of Slag Concrete in a Marine Environment," *ACI Materials Journal*, V. 105, No. 6, Nov.-Dec., pp. 628-634.

Titherington, M. P., and Hooton, R. D., 2004, "Chloride Resistance of High Performance Concretes Subjected to Accelerated Curing," *Cement and Concrete Research*, V. 34, No. 9, pp. 1561-1567. doi: [10.1016/j.cemconres.2004.03.024](https://doi.org/10.1016/j.cemconres.2004.03.024)

Togawa, K., and Nakamoto, J., 1989, "Study on the Effects of Blast-Furnace Slag on Properties of No-Slump Concrete Mixtures," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-132, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1401-1412.

U.S. Environmental Protection Agency, 1994, "Comprehensive Procurement Guidelines," *Federal Register*, V. 59, No. 76, Apr., pp. 18,853-18,914.

U.S. Environmental Protection Agency, 1996, "Comprehensive Guideline for Procurement of Products Containing Recovered Materials," Office of Environmental Policy and Assistance, RCRA/CERCLA Division (EH-413), 3 pp.

USACE, 2014, "Unified Facilities Guide Specifications, Division-03 Concrete," UFGS-03 31 01.00 10, May, 35 pp.

Van Oss, H. G., 2015, "Slag, Iron and Steel," *2013 Minerals Yearbook*, United States Geologic Survey, June, pp. 69.1-69.10. [http://minerals.usgs.gov/minerals/pubs/commodity/iron\\_&\\_steel\\_slag/](http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_slag/)

Vanden Bosch, V. D., 1980, "Performance of Mortar Specimens in Chemical and Accelerated Marine Exposure," *Performance of Concrete in Marine Environment*, SP-65, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 487-507.

Voinovitch, I.; Raverdy, M.; and Dron, R., 1980, "Ciment de Laitier Granule Sand Clinkers," *Proceedings, 7th International Congress on the Chemistry of Cement*, Septima, Paris, pp. 122-128.

Waterways Experiment Station (WES), 1953, "Tests of Trief Cement and Laboratory-Ground Water-Quenched, Blast-Furnace Slag Cement," *Miscellaneous Paper No. 6-39*, 12 pp.

Wimpenny, D. E.; Ellis, C. M.; and Higgins, D. D., 1989, "The Development of Strength and Elastic Properties in Slag Cement under Low Temperature Curing Conditions," *Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, SP-114, V. 2, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 1288, 1296.

Wood, K., 1981, "Twenty Years of Experience with Slag Cement," *Symposium on Slag Cement*, University of Alabama, Birmingham, AL.

Wood, S. L., 1992, "Evaluation of the Long-Term Properties of Concrete," *RD102*, Portland Cement Association, Washington, DC, pp. 14-15.

Wu, X., and Roy, D. M., 1982, "Zeta Potential Investigation During Hydration of Slag Cement," *Proceedings, M. R. S. Symposium*, Research Society, Boston, MA.









American Concrete Institute  
*Always advancing*

As ACI begins its second century of advancing concrete knowledge, its original chartered purpose remains “to provide a comradeship in finding the best ways to do concrete work of all kinds and in spreading knowledge.” In keeping with this purpose, ACI supports the following activities:

- Technical committees that produce consensus reports, guides, specifications, and codes.
- Spring and fall conventions to facilitate the work of its committees.
- Educational seminars that disseminate reliable information on concrete.
- Certification programs for personnel employed within the concrete industry.
- Student programs such as scholarships, internships, and competitions.
- Sponsoring and co-sponsoring international conferences and symposia.
- Formal coordination with several international concrete related societies.
- Periodicals: the ACI Structural Journal, Materials Journal, and Concrete International.

Benefits of membership include a subscription to Concrete International and to an ACI Journal. ACI members receive discounts of up to 40% on all ACI products and services, including documents, seminars and convention registration fees.

As a member of ACI, you join thousands of practitioners and professionals worldwide who share a commitment to maintain the highest industry standards for concrete technology, construction, and practices. In addition, ACI chapters provide opportunities for interaction of professionals and practitioners at a local level to discuss and share concrete knowledge and fellowship.

**38800 Country Club Drive**  
**Farmington Hills, MI 48331**  
**Phone: +1.248.848.3700**  
**Fax: +1.248.848.3701**

[www.concrete.org](http://www.concrete.org)



American Concrete Institute  
*Always advancing*

38800 Country Club Drive  
Farmington Hills, MI 48331 USA  
+1.248.848.3700  
[www.concrete.org](http://www.concrete.org)

The American Concrete Institute (ACI) is a leading authority and resource worldwide for the development and distribution of consensus-based standards and technical resources, educational programs, and certifications for individuals and organizations involved in concrete design, construction, and materials, who share a commitment to pursuing the best use of concrete.

Individuals interested in the activities of ACI are encouraged to explore the ACI website for membership opportunities, committee activities, and a wide variety of concrete resources. As a volunteer member-driven organization, ACI invites partnerships and welcomes all concrete professionals who wish to be part of a respected, connected, social group that provides an opportunity for professional growth, networking and enjoyment.

