

Guide to the Use of Slag Cement in Concrete and Mortar

Reported by ACI Committee 233

ACI 233R-17



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).

American Concrete Institute
3880 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

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†, 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

Chun Shi
M. 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

†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 only 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

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 Committee Reports, Guides, and Commentaries are intended to provide 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.

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—Tile upsets, 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 m³ (863,000 yd³) of concrete. The slag was ground wet and charged into the mixer as a thick slurry.

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

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

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

Until the 1950s, slag cement was used in two basic ways: as a raw material for the manufacture of portland cement, and as a cementitious material combined with portland cement, hydrated lime, gypsum, or anhydrite (Lewis 1981).

Since the late 1950s, use of slag cement as a separate cementitious material added at the concrete mixer with portland cement has gained acceptance in South Africa, Australia, the United Kingdom, Japan, Canada, and the United States, among other countries.

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

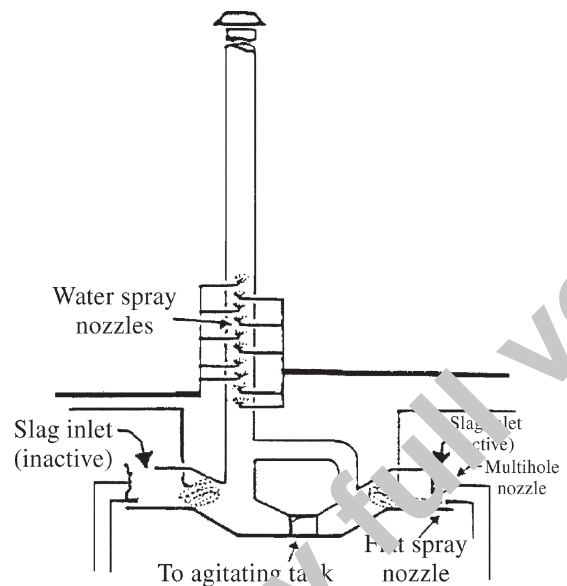


Fig. 1.4.2a—Configuration of blast-furnace slag water granulator to include steam condensing tower (Hogan and Meusel 1981).

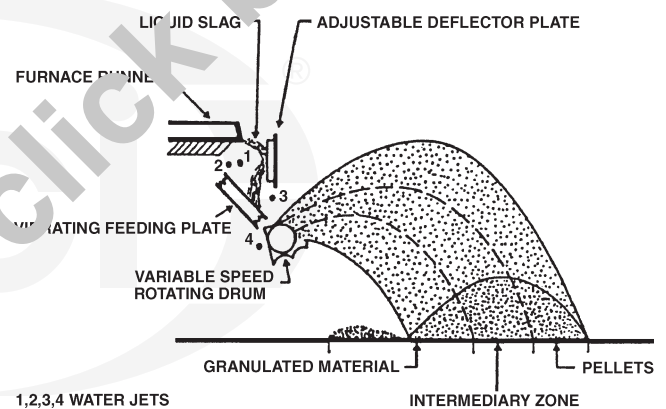


Fig. 1.4.2b—Blast-furnace slag palletization process, using a minimum of water usually applied at the feed plate (Hogan and Meusel 1981).

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).