

ACI ITG-10R-18

Practitioner's Guide for Alternative Cements

Reported by ACI Innovation Task Group 10



American Concrete Institute
Always advancing



Documents

Document Sharing Hub



Pracitioner's Guide for Alternative Cements

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, 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 the ACI Collection of Concrete Codes, Specifications, and Practices.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Practitioner's Guide for Alternative Cements

Reported by ACI Innovation Task Group 10

Lawrence L. Sutter, Chair

Mary U. Christiansen
Jonathan E. Dongell

James K. Hicks
R. Douglas Hooton

Kevin A. MacDonald
Claudio E. Manissero

Anol K. Mukhopadhyay
Deepak Ravikumar

As performance demands of concrete increase, and given recent initiatives to address the sustainability of construction, owners, architects, and engineers are actively seeking alternatives to portland cement for concrete. An alternative cement is intended to be a replacement for portland cement in some applications. In some cases, alternative cements may also be used in combination with portland or blended hydraulic cements. This document covers currently available and emerging alternative cements and is intended to provide information to help guide practitioners seeking to implement alternative cements.

Keywords: alkali-activated fly ash cement; alkali-activated glass cement; alkali-activated slag cement; alkali activation; alternative cements; calcium aluminate cement; calcium sulfoaluminate cement; carbonated calcium silicate cement; durability; functional addition; geopolymer; magnesium oxychloride cement; magnesium phosphate cement; reactive belite cement; specifications; supersulfated cement; sustainability; test method.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 1

- 1.1—Introduction, p. 1
- 1.2—Background, p. 2
- 1.3—Scope, p. 2
- 1.4—Organization of this guide, p. 2

CHAPTER 2—DEFINITIONS, p. 3

- 2.1—Definitions, 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 3—ALTERNATIVE CEMENT PROPERTIES AND APPLICATIONS, p. 3

- 3.1—Available alternative cement technologies, p. 3

CHAPTER 4—SELECTED CASE STUDIES, p. 6

- 4.1—Calcium aluminate cement (CAC), p. 7
- 4.2—Calcium sulfoaluminate (CSA), p. 8
- 4.3—Activated fly ash and slag, p. 8

CHAPTER 5—GUIDELINES FOR USE, p. 10

- 5.1—Mixture design, p. 10
- 5.2—Construction, p. 11
- 5.3—Design properties, p. 12

CHAPTER 6—SUMMARY, p. 12

CHAPTER 7—REFERENCES, p. 12

- Authored documents, p. 12

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

This guide is intended as an introduction for engineers, architects, contractors, and owners who are interested in using an alternative cement on a project, but lack experience with these materials. This guide assumes the reader has experience with conventional concrete materials and construction, and is seeking knowledge on how these new cement technologies compare to portland cement when used in concrete.

The alternative cement properties summarized in this document are those reported for properly designed and placed alternative cement concretes. As with all types of concrete, material quality, mixture design, curing method-

ACI ITG-10R-18 was adopted and published April 2018.

Copyright © 2018, 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 storage, retrieval, reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietor.

ology, and placement technique are all crucial to obtaining the desired properties; the examples presented are not universally applicable but are illustrative of what to expect from specific alternative cements.

1.2—Background

Portland cement concrete (PCC) is unrivaled when it comes to versatility and durability and, as such, is the most widely used man-made material on Earth. Countless civil engineering and architectural structures use concrete in their construction, including roads, bridges, public water and sanitary systems, and buildings. Almost 200 years of experience has resulted in a solid, practical understanding of how PCC works, and with the correct mixture design and materials, practitioners can manipulate concrete to easily meet the needs of society.

As engineers, architects, and contractors continue to push the bounds of what is possible in design and construction, materials must evolve as well, which is where alternative cements come in. To serve as an alternative to portland cement, a binder technology needs to offer demonstrable improvements when considering factors such as environmental impact, life-cycle cost (LCC), and performance. The use of an alternative cement is motivated by one or more of three main drivers:

1. Reduced cost—both initial cost and LCC
2. Reduced environmental impact
3. The need for specific properties unattainable with PCC

Improving the sustainability of construction is clearly one force driving the emergence of alternative cement concrete technologies. Increasingly, construction alternatives are being considered in terms of their LCC, in addition to or in place of initial cost. When it comes to LCC determination, the industry has considerable experience with PCC and can estimate the individual costs that contribute to the LCC. For some alternative cements, the industry still needs to develop that experience and establish life-cycle costs. A life-cycle cost is strongly intertwined with the material's functional performance and is inextricably linked to its durability. Given their recent development, long-term durability data are not available for all alternative cements.

As is the case with all manufacturing processes, portland cement production has environmental impacts that represent a cost to society. Chief among these are: 1) the energy-intensive nature of producing portland cement; and 2) the inherent release of greenhouse gas (GHG) emissions in the production process. A key advantage of alternative cement production is a significant reduction in environmental impact as compared to portland cement. The specific nature of the reduction varies between different alternative cement technologies. **Burris et al. (2015)** states manufacture of the alternative cements described in this document results in anywhere from 44 to 84 percent of the CO₂ associated with the production of an equal mass of portland cement.

Apart from sustainability considerations, in some applications an alternative cement concrete may offer enhanced functional performance when compared to PCC, and in those cases, the market value of the alternative cement concrete

may exceed that of PCC. In most cases, however, initial costs should be similar for an alternative cement to be considered for use. More importantly, for alternative cements to replace PCC in less-specialized applications, functional equivalence with PCC is required. Functional equivalence is required due to the empirical nature of the concrete design and construction environment. Demonstrated performance, both in the laboratory and in practice, is required to ensure that life-safety considerations are met when using alternative cement concrete in place of PCC. Demonstrating this performance to specifiers has been a challenge for alternative cement producers largely due to the lack of a clear testing protocol or, in some cases, the lack of applicable tests.

Another aspect of functional performance is constructability. To achieve the desired hardened properties, the concrete must be properly placed and cured in the field. This aspect limits the application of some alternative cements that require specific non-atmospheric curing regimes such as a CO₂-rich curing environment, or elevated temperatures. For other alternative cements, rapid setting and rapid strength gain, as compared to PCC, are principal value-added aspects of their performance. Constructability also depends on the availability of knowledgeable people to both place and adjust the mixture designs to achieve the desired performance. Therefore, it is necessary to have a workforce that is trained and able to proportion, test, mix, place, and cure these new materials.

1.3—Scope

This guide covers both currently available and emerging alternative cements, and is intended to aid people interested in using alternative cements in a project. A brief summary of each of the alternative cement technologies is provided, as well as selected case studies and a guideline for use that addresses mixture design as well as construction and design properties. References made to portland cement and portland cement production are for comparison purposes only. An in-depth discussion of portland cement is not within the scope of this guide.

1.4—Organization of this guide

This guide is organized into five chapters; a synopsis of each is presented below.

Chapter 1—Introduction and Scope: Describes the need for alternative cements and identifies the scope and objectives of this guide.

Chapter 2—Notation and Definitions: Defines terminology unique to alternative cements or not currently defined in *ACI Concrete Terminology*.

Chapter 3—Alternative Cement Properties and Applications: Summarizes the alternative cement technologies currently considered commercially available, as well as those in development.

Chapter 4—Selected Case Studies: Provides selected case studies to help illustrate how some of these materials have been used successfully.

Chapter 5—Guidelines for Use: Provides guidelines for issues to consider when deciding to use an alternative

cement including mixture design, construction, and design properties. Many of these issues can be resolved in dialogue with the alternative cement producer, although some will require testing prior to design or construction.

Chapter 6—Summary: Provides a brief summary of the document.

CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology.” Definitions provided herein complement that source.

2.1—Definitions

alkali activation—the process of using an alkali-based solution to cause the dissolution of an aluminosilicate precursor and initiating the chemical reactions leading to the formation of reaction products.

alkali activator—an alkali-based solution that causes alkali activation.

Note: Examples of alkali activators include concentrated sodium hydroxide and sodium silicate solutions. Molar strengths of up to 10M are typical.

alternative cement—an inorganic cement that can be used as a complete replacement for portland or blended hydraulic cements, and that is not covered by applicable specifications for portland or blended hydraulic cements.

Note: An alternative cement or alternative cement blend could provide better performance than that of portland or blended hydraulic cement in some applications. An alternative cement, however, might not perform adequately as a replacement for portland or blended hydraulic cement in every application. In some cases, alternative cements can also be used in combination with portland or blended hydraulic cements.

functional addition—a substance other than water that is added to, or combined with, a material that is not hydraulic and causes a cementitious reaction to occur or accelerate.

geopolymer—an alternative cement produced from aluminosilicate precursors that form nonhydrated cementitious reaction products by alkali activation.

precursor—a solid raw material reacted with a functional addition to form an alternative cement.

CHAPTER 3—ALTERNATIVE CEMENT PROPERTIES AND APPLICATIONS

3.1—Available alternative cement technologies

For discussion, the technologies are grouped based on similar cement production factors. Clinkered alternative cements use production technologies similar to portland cement, but with process changes that affect the environmental footprint of the product. Often, these process changes lead to material properties that affect aspects of the related alternative cement concrete such as cost or performance. Clinkered alternative cements in some cases are produced with precursor materials similar to portland cement raw materials, while in other cases alternative raw materials are used. In some cases, they differ from portland cement

Table 3.1—Summary of alternative cement technologies discussed

Clinkered alternative cements	Calcium aluminate Reactive belite Calcium sulfoaluminate Carbonated calcium silicate (emerging technology)
Calcined alternative cements	Magnesium oxychloride Magnesium phosphate Magnesium ammonium phosphate Magnesium potassium phosphate
Non-clinkered alternative cements	Alkali-activated Fly ash Slag Recycled glass (emerging technology) Supersulfated cement

in terms of production technology, such as kiln operating temperatures. Non-clinkered alternative cements often beneficially use industrial by-products as a precursor material and require the addition of an activating solution.

Table 3.1 provides a summary of the commercially available or emerging alternative cement technologies discussed in this guide.

3.1.1 Clinkered alternative cements—Clinkered alternative cements are manufactured using production technologies similar to those used to manufacture portland cement. With the exception of carbonated calcium silicate, the materials all react through hydration (that is, they are hydraulic cements). However, the resulting materials have chemical and physical properties that are notably different than portland cement, and in some cases require completely different approaches to implementation (for example, different curing regimes).

3.1.1.1 Calcium aluminate cements—Calcium aluminate cements (CACs) are produced using raw materials different from portland cement production. When CAC is placed in contact with water, hydration reactions occur, as happens with portland cement. However, the reaction products formed are completely different given the different cement composition and CAC use must be approached understanding these differences. When 100 percent CAC is used, the hydration products formed are thermodynamically unstable and, with time, at ambient temperature, pressure, and humidity, these hydration products convert to thermodynamically stable forms with a significant loss of strength. This “conversion” process must be accounted for and the final converted strength must be used in design to ensure predictable performance. Assessing conversion is done through performance testing. Technical support for mixture design and conversion testing should be obtained from the CAC provider for first-time users of this product. By blending CAC with portland cement or other products, this conversion process is readily controlled.

Calcium aluminate cements resist sulfate attack, are abrasion-resistant, and are sometimes combined with synthetic aggregate made from CAC to produce a highly resistant material for use in dam spillways and industrial floor slabs (Scrivener and Capmas 2003). Calcium aluminate cements are also generally considered to be resistant to alkali-silica

reaction, given the hydration products are different from those of portland cement. Specifically, there is no calcium hydroxide (CH) formed in the hydration reaction, the pH of the pore solution is lower (pH 11.5 to 12.5) and, therefore, CAC does not promote dissolution of silica (SiO_2) in reactive aggregates.

3.1.1.2 Reactive belite cement—A reactive belite cement (RBC) is produced from a modified portland cement clinker that has a significantly lower alite content and a significantly higher belite content. This means if used by itself as a hydraulic cement, early strengths would be very low but later strengths, such as 28-day strengths, may be acceptable (Chatterjee 1996). The advantage of RBC clinker is that a lower kiln temperature can be used to produce the materials, resulting in less fuel consumption, less raw material use (for example, limestone), and lower CO_2 and NO_x emissions. Because of the low early strengths, RBC is rarely used without some modification to improve the early strength. The most common modification results in calcium sulfoaluminate cement (CSA), which is discussed in the next section.

3.1.1.3 Calcium sulfoaluminate cements—One approach to increasing the early strength of RBC is to add a reactive component such as calcium sulfoaluminate (Quillin 2001). Calcium sulfoaluminate cements are not new; they contain as a primary phase ye'elimite ($\text{Ca}_4\text{Al}_6\text{SO}_{16}$ or $\text{C}_4\text{A}_3\bar{\text{S}}$ in cement chemistry notation), which was used by Alexander Klein in the 1960s as an additive to portland cement to form expansive cement and is sometimes called Klein's Compound (Klein 1966). These cements can exhibit rapid setting, rapid strength gains, and expansion. In practice, these properties can be controlled through manipulating the composition of the cement and through the addition of chemical retarders.

Concretes made using CSA generally show excellent sulfate resistance (Quillin 2001). Under natural and accelerated conditions, carbonation rates for CSA concrete are high when compared with PCC made using similar mixture designs (Quillin 2001). Therefore, corrosion of reinforcement could be an issue for concrete made using CSAs. The rate of carbonation, however, can be lowered with the use of appropriate water-reducing admixtures. The mechanical properties and durability of CSA concrete are reported to rival portland cement (Quillin 2001), although additional field experience is needed to fully vet the long-term material performance.

Calcium sulfoaluminate cements are used for some structural applications and are especially well-suited for precast and cold weather applications, which take advantage of the rapid strength gain of these materials (Su et al. 1997).

3.1.1.4 Carbonated calcium silicates (emerging technology)—Carbonated calcium silicate cement (CCS) is a non-hydraulic cement. As the name implies, the solidification process used is carbonation. Water is used as the medium for the process and it is not incorporated into the final hardened cement paste, as is the case with portland cement hydration. Carbonated calcium silicate cement clinker is produced using the same raw materials and rotary kilns used for portland cement clinker production, but the kiln is operated at a lower temperature. The resulting clinker

is different in composition as compared to portland cement clinker. The production of CCS clinker results in significant reductions in CO_2 emissions as well as a reduced embodied energy. Carbonated calcium silicate cement is an emerging technology that is not yet fully commercialized.

Carbonated calcium silicate cement requires curing in a CO_2 -rich environment and, therefore, special equipment is required for curing. Unlike the hydration reactions in portland cement, the carbonation reaction in CCS is a relatively rapid process. Full curing of CCS-based concrete can occur in less than 10 to 24 hours (DeCristofaro et al. 2017).

3.1.2 Calcined alternative cements—Calcined alternative cements differ from portland cement in terms of production technology and are produced from raw materials not used for portland cement production. Calcined alternative cements are a combination of a calcined magnesite rock and a crosslinking agent that, when combined, react to form a solidified binder matrix.

3.1.2.1 Magnesium oxychloride cement—Magnesium oxychloride cement (MOC) was developed by Stanislas Sorel in 1867 (Sorel 1867) and is also referred to as Sorel or magnesite cement (Phair 2006; Valek et al. 2012). Magnesium oxychloride cement is not a hydraulic cement. The process of hardening occurs through an acid-base reaction. The main bonding phases found in hardened MOC pastes are magnesium hydroxide.

During initial curing, MOC is not stable in prolonged contact with water. Leaching of magnesium chloride, with reversal of the reaction and loss of strength can result (Lu et al. 1994). Over a period of time, atmospheric CO_2 reacts with magnesium oxychloride to form a surface layer that slows the leaching process. Eventually, additional leaching leads to the formation of hydromagnesite, which is insoluble and enables the cement to maintain structural integrity (Cole and Demediuk 1955). A variety of additives have been developed that will significantly slow down or block water penetration during early ages, or expedite formation of hydromagnesite.

The set time for neat MOC paste can vary from a few hours to 48 hours (Yadav et al. 2013). Curing is affected by temperature, air flow, and humidity conditions. While heating could increase the rate of hardening, care must be taken not to overheat the concrete to avoid cracking of the material (Yadav et al. 2012). After set, no further curing is necessary.

Being an acid/base reaction, MOC paste develops a significant heat of reaction. The mixtures, therefore, can develop temperatures of up to 140 to 176°F (60 to 80°C), or in some cases, temperatures above 212°F (100°C) have been reported (Newman et al. 1952). Care should be taken when handling neat paste to avoid thermal damage of substrates and forms and to avoid personal injury. Temperature evolution is significantly decreased when fillers/aggregates are added to the paste, resulting in mixtures that are safe to handle and place. Also, the evolved heat dissipates quickly due to the high temperature conductivity of the material.

Concrete mixtures prepared with MOC, when properly formulated, can have high compressive strength, such as