Guide to the Selection and Use of Hydraulic Cements

Reported by ACI Committee 225

ACI 225R-16

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First Printing
September 2016
ISBN: 978-1-945487-16-3

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Reported by ACI Committee 225

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*The committee would like to acknowledge B. Blair and M. D. A. Thomas for their contributions in the development of this guide.

Cement is the most active component of concrete and usually has the greatest unit cost; therefore, its selection and proper use is imperative to attaining the desired balance of properties and cost for a particular concrete mixture. Selection should include consideration of the cement properties in relation to the required performance of the concrete. This guide covers the influence of cement on the properties of concrete, summarizing the composition and availability of commercial hydraulic cements and the factors affecting their performance in concrete. It includes a discussion of cement types, a brief review of cement chemistry, the influences of chemical admixtures and supplementary cementitious materials, and the effects of the environment on cement performance, and reviews the sustainability aspects for the use and manufacture of portland cement. Cement storage, delivery, sampling, and testing of hydraulic cements for conformance to specifications are addressed. Users will learn to recognize when a readily available, general-purpose cement will perform satisfactorily or when conditions require selection of a cement that meets additional requirements.

Keywords: admixture; blended cement; calcium-aluminate cement; cement storage; cement types; chemical analysis; hydraulic cement; pozzolan; physical properties; portland cement; slag cement; supplemental cementitious materials; sustainability.

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ACI 225R-16 supersedes ACI 225R-99 and was adopted and published September 2016.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

This guide assists specifiers and designers in choosing appropriate cement for specified concrete applications. Although hydraulic cements are only one ingredient of a concrete mixture, they are the active ingredient and, therefore, play a key role in the long-term viability of the structure, floor, or pavement. Cement choice depends on many variables, such as the service conditions for which the concrete is designed, properties of other materials used in the mixture, or the performance characteristics of the concrete required during or shortly after placement.

Cement paste is the binder in concrete or mortar that holds the fine aggregate, coarse aggregate, or other constituents together in a hardened mass. The term "hydraulic" in this guide refers to the basic mechanism by which the hardening of the cement takes place—a chemical reaction between the cement and water. The term also differentiates hydraulic cement from binder systems that are based on other hardening mechanisms, as hydraulic cements can harden underwater.

Concrete properties depend on the quantities and qualities of its constituents. Because cement is the most active component of concrete and usually has the greatest unit cost, its selection and proper use are fundamental in obtaining the most economical balance of properties desired for a particular concrete mixture. Most cements will provide adequate levels of strength and durability for general use. Some provide higher levels of certain properties than are needed in specific applications.

1.2—Scope

This guide summarizes information about the composition, availability, and factors affecting the performance of commercial hydraulic cements. It also provides information regarding:

a) Cement selection, whether a cement is readily available, and if conditions require a general-purpose cement or a special cement

b) How the chemical and physical characteristics of a cement can affect certain properties of concrete

c) How interaction of cements with various additives, admixtures, and mixture designs can affect concrete

This guide only deals with hydraulic cements manufactured under North American standards (ASTM International, American Association of State Highway and Transportation

Officials [AASHTO], and Canadian Standards Association [CSA]). For information on other hydraulic cement standards, the user is directed to local specifications and building codes.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

Cement phases referred to throughout this guide follow the cement chemists' notations as follows:

A = Al_2O_3
C = CaO
$\overline{C}$ = CO_2
F = Fe_2O_3
H = H_2O
M = MgO
S = SiO_2
$\overline{S}$ = SO_3
tricalcium silicate: $3CaO{\cdot}SiO_2 = C_3S$
dicalcium silicate: $2CaO{\cdot}SiO_2 = C_2S$
tricalcium aluminate: $3CaO{\cdot}Al_2O_3 = C_3A$
tetracalcium aluminoferrite: $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3 = C_4AF$

Tricalcium silicate, Ca_3SiO_5, in conventional notation becomes $3CaO{\cdot}SiO_2$ in oxide notation, or C_3S in cement chemists' notation. Simple oxides, such as CaO or SiO_2, are often written in full.

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," https://www.concrete.org/store/productdetail.aspx?ItemID=CT16.

Equivalent alkali in hydraulic cement is the total of sodium and potassium oxides as calculated from the chemical analysis, and using the formula: $Na_2Oeq = \%\ Na_2O + 0.658\%K_2O$ (ASTM C219).

CHAPTER 3—CEMENT TYPES, AVAILABILITY, AND SELECTION

Selection of cement is an important consideration when proportioning mixtures for specific project requirements and intended use. It is important that the specification for hydraulic cements be appropriate for the project and the hydraulic cements available in the area. Factors such as exposure conditions and desired properties can often require specific cement types based on the chemistry or physical properties. Specific cements may be available that are designed for applications where performance requirements cannot be achieved with ordinary portland cement.

3.1—Portland and blended hydraulic cements

A majority of the cement used for concrete construction in the United States is either portland cement, manufactured to meet the requirements of ASTM C150/C150M, blended hydraulic cement manufactured to meet the requirements of ASTM C595/C595M, or performance-based hydraulic cement manufactured to meet the requirements of ASTM C1157/C1157M. Tables 3.1a and 3.1b include basic characteristics of these cements as listed in ASTM. Other portland cement specifications can be found in AASHTO M 85 or, for Canada, in CSA-A3001. Blended cements are also specified under the AASHTO M 240 requirements. For more on hydraulic cement specifications and selection, refer to 3.4.

Table 3.1a—Characteristics of portland cements*

Type*	Description	Optional characteristics†
I	General use	1, 4
II	General use; moderate sulfate resistance	1, 4
II (MH)	General use; moderate heat of hydration	1, 4
III	High-early-strength	1, 2, 3
IV	Low heat of hydration	4
V	High sulfate resistance	4, 5

*For cements specified in ASTM C150/C150M.

†Optional characteristics:

1. Air entraining (A)
2. Moderate sulfate resistance: C_3A maximum, 8 percent
3. High-sulfate resistance: C_3A maximum, 5 percent
4. Low alkali: maximum of 0.60 percent alkalies, expressed as Na_2O equivalent
5. Alternative limit of sulfate resistance is based on expansion tests of mortar bars

Portland cements are manufactured by a process that begins by combining a source of lime such as limestone, a source of silica and alumina such as clay, and a source of iron oxide such as iron ore. The properly proportioned mixture of the raw materials is finely ground and then heated to approximately 2700°F (1480°C) for the reactions that form cement phases to take place. The product of a cement kiln is portland cement clinker. After cooling, the clinker is ground with calcium sulfate (gypsum); processing additions; and, in many cases, limestone to form a portland cement. Processing additions are organic or inorganic materials used in the manufacture of cements that are added at the finish mill. Their use is governed by ASTM C465. Processing addition rates for portland cements are specified in ASTM C150/C150M. The specific gravity of portland cement will vary slightly depending on the amounts of limestone, gypsum, and inorganic processing addition added to the clinker (for further reference on inorganic process addition refer to Taylor [2008]). Most of these additions are less dense than clinker and tend to reduce the specific gravity of the portland cement. When proportioning concrete mixtures, unless an actual measurement of the specific gravity of the cement has been made, 3.15 has been used for portland cements (Kosmatka and Wilson 2011). As the amount of processing additions increase, the specific gravity value has been found to decrease.

Blended hydraulic cements are usually made by intergrinding portland cement clinker with calcium sulfate (gypsum); processing additions; and a quantity of a suitable material such as slag cement, fly ash, limestone, silica fume, or raw or calcined natural pozzolans. They may also be made by blending the finely ground ingredients, or by a combination of blending and intergrinding. The specific gravity of a blended cement will vary with the type and amount of material(s) that is interground or interblended.

Table 3.1b—Characteristics of blended hydraulic and performance-based hydraulic cements

ASTM C595/C595M Type	Name	Blended ingredients range, percent by mass			Optional characteristics*
		Pozzolan	Slag cement	Limestone	
IP	Portland-pozzolan cement	1 to 40	—	—	1, 2, 3, 4, 5, 6
IS	Portland blast-furnace slag cement	—	1 to 95	—	1, 2, 3, 4, 6
IL	Portland-limestone cement	—	–	5 to 15	1, 4, 5, 6
IT	Ternary blended cement†	1 to 40	1 to 95	5 to 15	1, 2, 3, 4, 5, 6

ASTM C1157/C1157M Type	Name	Optional characteristics*
GU	General use	1, 6
HE	High early strength	1, 6
MS	Moderate sulfate resistance	1, 6
HS	High sulfate resistance	1, 6
MH	Moderate heat of hydration	1, 6
LH	Low heat of hydration	1, 6

*Optional characteristics that can be specified for various cement types:

1. Air-entraining (A)
2. Moderate sulfate resistance (MS)
3. High sulfate resistance (HS)
4. Moderate heat of hydration (MH)
5. Low heat of hydration (LH)
6. Suitability for use with alkali-silica reactive aggregate

†Ternary blended cements include two of the ingredients (pozzolan, slag cement, or limestone) in the ranges noted, but not all three.

For specification purposes, portland and blended hydraulic cements are designated by type depending on their chemical composition and properties. The availability of a given type of cement may vary widely among geographical regions. Commonly used descriptions of portland and blended cements are given in Tables 3.1a and 3.1b. The use of blended cements is growing in response to the demand for concrete requiring special properties, energy conservation, and raw materials.

3.2—Special-purpose

In addition to portland and blended cements, other hydraulic cements are available for specialized uses (Table 3.2). Other cement types are only touched upon, as their availability is limited in some regions.

3.2.1 *Masonry cements*—These are used in masonry mortars. They are specified in ASTM C91/C91M and their use is covered by ASTM C270 and ACI 530/530.1. Plastic and mortar cements are also used in mortars and specified in ASTM C1328/C1328M and ASTM C1329/C1329M, respectively. In Canada, masonry and mortar cements are specified in CSA-A3002.

Certain portland cements can give the finished product special colors, such as white or buff, which are used for architectural purposes. White and buff cements are usually furnished to meet ASTM C150/C150M specifications.

3.2.2 *Modified portland cements*—Modified portland cements as described in ASTM C90, which are sometimes referred to as block cements, are manufactured to meet the needs of the concrete masonry unit manufacturing industry.

3.2.3 *Expansive or shrinkage-compensating cements*—These are designed to expand a small amount during the first few days of hydration to offset the effects of later drying shrinkage. Their purpose is to reduce cracking resulting from volume decrease due to shrinkage or to cause stressing of reinforcing steel (ACI 223R). Those manufactured in the United States depend on the formation of a higher-than-usual amount of ettringite during hydration of the cement to cause the expansion (ASTM C845/C845M). The expansive ingredient, an anhydrous calcium sulfoaluminate, can be purchased separately. Magnesium or calcium oxide may also be used as expansive agents.

3.2.4 *Rapid-hardening hydraulic cements*—These are designed to give rapid strength gain during the first 24 hours of hydration. Four categories of performance are specified in ASTM C1600/C1600M with strength requirements from 1.5 to 24 hours. Rapid-hardening hydraulic cements can be used in the same application as portland and blended cements, and usually include processing or functional additions. They are typically used for repair applications or where very rapid strength gain is needed.

3.2.5 *Regulated-set cements*—Regulated-set cements are similar in composition to portland cements, except that the clinker from which they are made contains a small quantity of fluorine. They are formulated to have unusually short setting times followed by development of a moderate early strength.

3.2.6 *Well cements*—Well cements are manufactured specifically for use in sealing spaces between well casings and linings, and the surrounding geological formations. They are usually required to comply with API 10A. These

Table 3.2—Miscellaneous or special-purpose cements

Type	Description or purpose	ASTM specification
White cement	White architectural cement	C150/C150M*
Buff cement	Buff architectural cement	C150/C150M*
Expansive cement, Type E-1†	Expansive hydraulic cement	C845/C845M
Regulated-set cement	For use where rapid setting and moderate early strength development is needed	None
Rapid-hardening hydraulic cements	For use where early strength development is needed	C1600/C1600M
Oil-well cements, Types A through H, J‡	Hydraulic cements used for oil-well casings and linings	None
Masonry cement, Types M, S, and N	For use in mortar for masonry, brick and block construction, and stucco	C91/C91M
Plastic cement	For use in exterior stucco applications	C1328/C1328M
Mortar cements Types M, S, and N	For use in mortar for masonry, brick, and block construction	C1329/C1329M
Calcium-aluminate cement	For use in refractory, high-early-strength, and moderately acid-resistant concretes	None
Block cement	For use in making concrete masonry units	C1157/C1157M, C595/C595M, C150/C150M
Magnesium phosphate cement	Nonportland cement for use where rapid hardening is needed	None

*Although white and buff cements are not listed specifically in ASTM C150/C150M, they could meet the requirements of ASTM C150/C150M as indicated by the manufacturer.

†Three kinds are identified by letters K, M, and S.

‡These are covered by American Petroleum Institute (API 10A).

cements specified in API 10A can also meet ASTM specifications; for example, Class G well cements meeting API 10A often meet the requirements of ASTM C150/C150M, Type II or V. For very-high-temperature wells, less--reactive cements are sometimes used, such as mixtures of dicalcium silicate and finely ground silica.

3.2.7 *Calcium-aluminate cements*—Calcium-aluminate cements (Appendix A) are intended primarily for refractory applications and are designated as being of low, intermediate, or high purity. The purity level of the calcium-aluminate cement is based on iron content in the low-purity cement and free alumina content in the high-purity cement. Low-purity calcium aluminate cements are also used for concretes that are to be exposed to mild acids and certain industrial wastes. Other possible applications are self-leveling floors, and patching and repair when very high early strengths are needed.

3.2.8 *Plastic cements*—Plastic cements (ASTM C1328/C1328M) are formulated for use in mortars for stucco. They are portland cements modified by small amounts of additives that cause the mortars made from them to have flow properties that aid stucco applications.

3.2.9 *Waterproof cements*—These are portland cements interground with stearic acid or other water repellents with the objective of imparting water repellency to concrete containing them.

3.2.10 *Ultrafine cements*—These are of fine particle size with a 50 percent by mass distribution of the particles having a mean diameter of less than 0.0002 in. (5 µm) and are usually composed of blends of portland and slag cements. These small-sized particle systems are required in geotechnical applications and repairing relatively large cracks and other concrete applications where permeation grouting of fine sands, underground strength, or water control in finely fractured rock formations is needed.

3.2.11 *Photocatalytic cements*—These contain photocatalysts, often as engineered nanoparticles, which in the presence of water, oxygen, and ultraviolet light, and visible light, produce strong oxidizing agents. The net effect of the surface-initiated reactions can impart new functionality to cement-based materials, including self-cleaning, biocidal, hydrophobicity, hydrophilicity, and smog-abatement functionality (Giannantonio et al. 2009; Husken et al. 2009; Bowering et al. 2006; Kawakami et al. 2007; Diamanti et al. 2008).

3.3—Research and development

Given the broad use of cement worldwide and the ever-increasing demands for enhancements in properties and performance, research and development has produced continued innovations in cements. For example, over the past decade, many innovations increasing the sustainability of cement have been introduced (Chapter 10). Another key area of innovation is the exploration of the potential for nanotechnology to improve cement and concrete performance. Some research has explored the incorporation of nano-sized materials (Sobolev et al. 2012). These nanoparticles including, for example, nanotubes, can graft molecules onto cement particles or cement phases to promote specific interfacial interactions and provide surface functionality. These composites can have a range of novel properties, such as low electrical resistivity, self-sensing capabilities, self-cleaning, self-healing, high ductility, and self-control of cracks.

3.4—Rational approach to selection

The goal of the specifier is to provide specifications that ensure that proper amounts and types of cement are used