ACI Education Bulletin E3-01

CEMENTITIOUS MATERIALS FOR CONCRETE

Developed by Committee E-701
Materials for Concrete Construction

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CHAPTER 1—INTRODUCTION

Concrete is made from a properly proportioned mixture of hydraulic cement, water, fine and coarse aggregates, and often, chemical or mineral admixtures. The most common hydraulic cement used in construction today is portland cement. Though other types exist, portland cement is the most abundant and the focus of this document. Exceptions are noted otherwise. The successful use of concrete in construction depends not only on knowing the right proportions of materials to use for a particular job, but also, knowing how to select the right materials. This requires a knowledge of the properties of each of the materials and understanding the tests used to measure those properties.

The selection and characterization of hydraulic cement and cementitious mineral admixtures are the subjects of this bulletin, while aggregates, admixtures, and concrete characteristics are discussed in companion volumes. There are several varieties of hydraulic portland cement, as recognized by the American Society for Testing and Materials (ASTM), which vary in their properties. A hydraulic cement is defined as a cement that sets and hardens by chemical reaction with water and is capable of doing so underwater. In the following chapters we will review the composition and properties of the various portland cements, discuss the tests used to evaluate a cement, and consider how cement properties influence the performance of the concrete.

The name "portland" originates from a trade name used by Joseph Aspdin in 1824 to describe the new cement he patented that year in England. He claimed that the artificial stone (concrete) made with his cement was similar in appearance to portland stone, a high-quality limestone used in construction during that time period. Although portland cement dates from Aspdin's patent in 1824, its roots can be traced back to ancient times, where several famous landmarks of the Roman era owe their survival to the cementing qualities of the forerunner to portland cement.

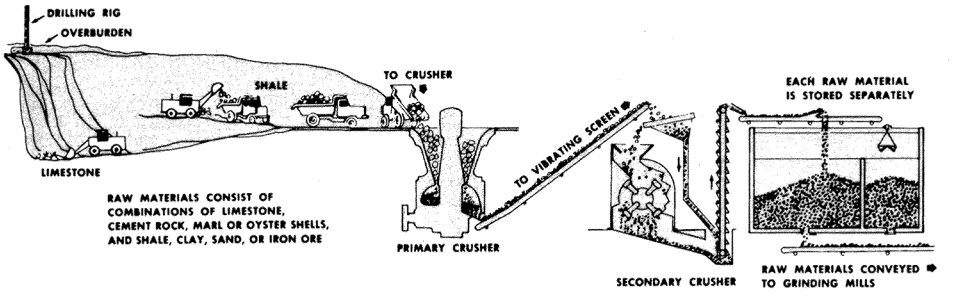
The portland cement industry quickly spread in England. By 1890, there was a flourishing export business to the U.S. The fledging U.S. industry founded by David Saylor at Coplay, Pa., in 1871, soon captured the domestic market. U.S. production rose from 60,000 tons per year in 1890, to 1.7 million tons in 1900, and by 1915 had increased to 15.5 million tons. Today, about 106 million metric tons (118 million tons) of portland cement are used each year in the U.S. Cement manufactured outside of the U.S. and imported accounts for 15 to 25% of the annual U.S. cement usage. In the past, cement production was measured in tons (2000 lb) and now it is measured in metric tons (1000 kg). A metric ton, or megagram (Mg), is equal to 1 million grams, and is about 10% more than a U.S. ton.

This document is an introductory document on the topic of commonly used Cementitious Materials for Concrete. This primer describes the basic uses of these materials. It is targeted at those in the concrete industry not involved in the determination of the specific mixture proportions of concrete or in calculating the behavior properties of the concrete. Students, craftsmen, inspectors, and contractors may find this a valuable introduction to a complex topic. The document is not intended to be a state-of-the-art report, users guide, or a technical discussion of past and present research findings on the subject. More detailed information is available in ACI Committee reports ACI 225R, "Guide to the Selection and Use of Hydraulic Cements," ACI 232.2R, "Use of Fly Ash in Concrete," ACI 233R, "Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete," and ACI 234R, "Guide for the Use of Silica Fume in Concrete."

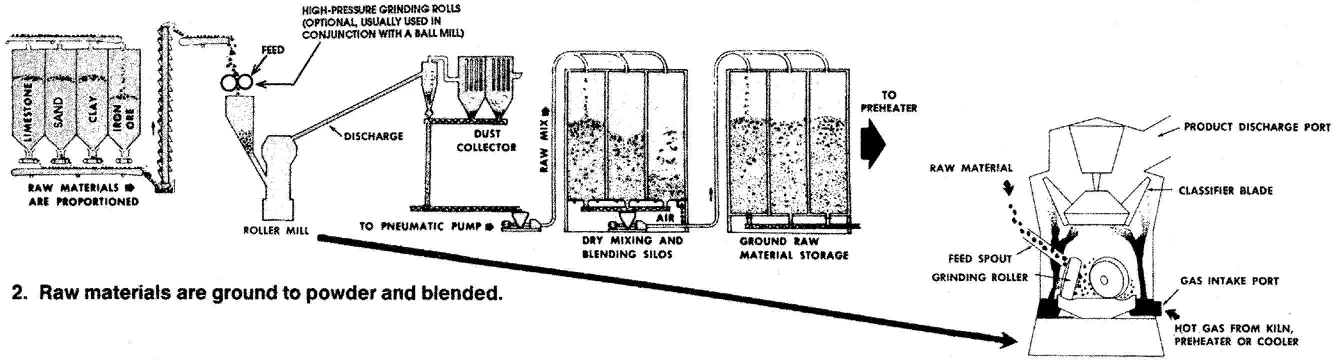
CHAPTER 2—MANUFACTURE OF PORTLAND CEMENT

Portland cement is a finely ground gray powder chemically formed by combining raw materials containing calcium oxide (CaO), silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), heating this mixture to a high temperature, and then grinding the resulting material, called clinker, with a small quantity of calcium sulfate ($CaSO_4$).

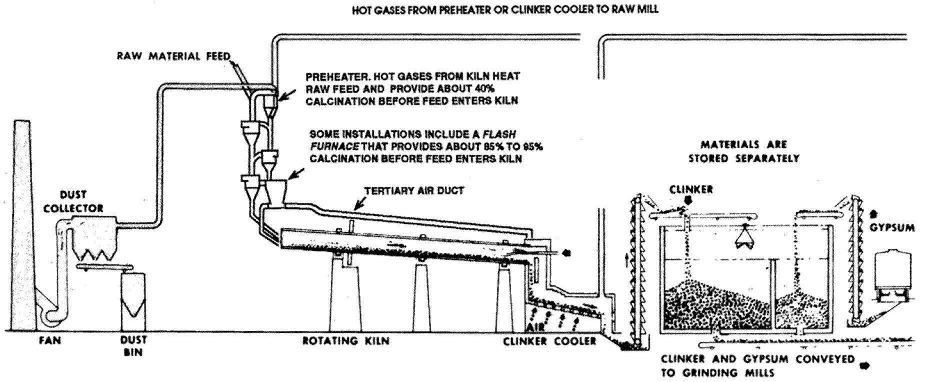
In principle, the manufacture of portland cement is simple. It is made from abundant raw materials. Intimately blended raw materials, usually limestone and clay, are heated in a kiln to 1400 to 1600 C (2550 to 2900 F), the temperature at which these materials chemically interact to form the cementitious compounds in portland cement. Considerable attention is paid to the various stages of processing to maintain good quality control. This processing requires 60 to 80 separate and continuous operations, the use of a great deal of heavy machinery and equipment, and the consumption of large amounts of fuel and electrical energy.



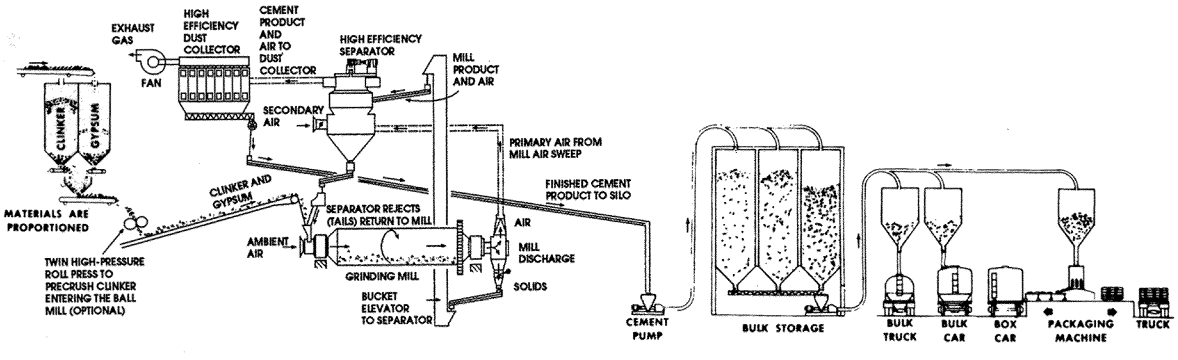
1. Stone is first reduced to 125 mm size, then to 20 mm, and stored.



2. Raw materials are ground to powder and blended.



3. Burning changes raw mix chemically into cement clinker. Note four-stage preheater, flash furnaces, and shorter kiln.



4. Clinker with gypsum is ground into Portland cement and shipped.

Fig. 2.1—New technology in dry-process cement manufacture. (Reproduced from Design and Control of Concrete Mixtures, *13th Edition, Portland Cement Association, Skokie, Ill., revised 1992.)*

Table 2.1—Typical sources of raw materials used in portland cement manufacture

Lime (CaO)	Iron (Fe_2O_3)	Silica (SiO_2)	Alumina (Al_2O_3)	Calcium sulfate
Alkali waste	Blast-furnace flue dust	Calcium silicate	Aluminum ore refuse	Anhydrite ($CaSO_4$)
Calcite	Clay	Cement rock	Bauxite	Hemihydrate ($CaSO_4 \cdot 1/2H_2O$)
Cement rock	Iron ore	Clay	Cement rock	Gypsum ($CaSO_4 \cdot 2H_2O$)
Chalk	Mill scale	Fly ash	Clay	—
Clay	Ore washings	Fuller's earth	Copper slag	—
Dolomite	Pyrite cinders	Limestone	Fly ash	—
Limestone	Shale	Loess	Fuller's earth	—
Marble	Fly ash	Marl	Granodiorite	—
Marl	—	Ore washings	Limestone	—
Seashells	—	Quartzite	Loess	—
Shale	—	Rice hull ash	Ore washings	—
Slag	—	Sand	Shale	—
—	—	Sandstone	Slag	—
—	—	Shale	Staurolite	—
—	—	Slag	—	—
—	—	Traprock	—	—

Note: As a generalization, probably 50% of all industrial by-products have potential as raw materials for portland cement manufacture.

Typical steps in the manufacture of portland cement are illustrated in Fig. 2.1. Each manufacturer of portland cement uses a trade or brand name under which it is sold, but the material is made by the same general processes to conform to the applicable requirements for the type of cement.

2.1—Raw material preparation

The manufacture of portland cement requires blending raw materials to obtain appropriate proportions of lime (CaO), silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). High-quality cements require raw materials of proper chemical composition and proportioned to precise quantities. Limestone, which consists primarily of calcium carbonate, is the most common source of lime, although other raw materials such as dolomite, chalk, shell deposits, and calcareous muds are used for this purpose. The location of cement plants is most often determined by the occurrence of suitable calcareous (lime-rich) deposits, and proximity to the market area. A suitable source of silica can usually be obtained close at hand. Iron-bearing aluminosilicates are often used as the primary source of silica. Clays or silts are preferred since they are already in a finely divided state; but shales, schists, and other argillaceous rocks are also used. Typical sources of these materials and their chemical compounds are given in Table 2.1.

A nearby quarry is the source of the basic material. The raw material is transported to the primary crusher by truck or rail. Upon leaving the primary crusher, the material is then conveyed to a secondary crusher system where it is reduced to a maximum size of usually less than 25 mm (1 in.). The crushed material is then stored in a raw material storage facility.

Raw materials are carefully proportioned and ground in roller presses or ball mills to a fineness similar to face powder. The ground material is then transported by pneumatic means through a pipeline to storage and blending silos. The material is constantly blended and checked for uniform chemical composition. The object of processing the raw materials is to ensure that the raw feed entering the kilns is of constant composition, finely divided, and chemically well balanced. This results in a cement of uniform composition and predictable properties. A uniform mixture also ensures that the kiln temperature can be kept fairly constant, near the optimum burning temperature.

2.2—Pyroprocessing

Once the raw feed has been satisfactorily ground and blended, it is ready to enter the kiln where pyroprocessing (burning) occurs. The rotary kiln is a long steel cylinder inclined a few degrees from the horizontal, and rotated at 60 to 200 rpm about its axis. Modern kilns are up to 6 m (20 ft) in diameter and over 180 m (600 ft) long, with a production capacity exceeding 5000 tons/day. The raw feed enters at the high end and the combination of rotation and inclination slowly moves the material the length of the kiln. Burning fuel, consisting of powdered coal, fuel oil, or gas, is forced into the lower end of the kiln, producing temperatures of 1400 to 1600 C (2550 to 2900 F) in the hottest part of the kiln. As the raw feed moves through the kiln, water and carbon dioxides are driven off from the constituents in the form of gases (calcination). The residual oxides recombine in the hottest part of the kiln, the clinkering zone, to form new chemical compounds. Heating to these high temperatures consumes large quantities of energy, much of which is lost with the exiting gases. Often the heated exhaust gases are used to raise the temperature of the incoming feed in special heat exchangers called preheaters.

2.3—Final processing

Material exiting the kiln is known as clinker; dark-gray, porous nodules (13 to 50 mm [1/2 to 2 in.]) in diameter that are still hot. The clinker is cooled by forced air, then conveyed to storage or immediately to ball mills where it is ground to the a fine gray powder. A small amount of gypsum ($CaSO_42H_2O$), hemihydrate: ($CaSO_4 \cdot 2H_2O$), hemihydrate ($CaSO_4 \cdot 1/2H_2O$), or anhydrite ($CaSO_4$) is interground with the clinker in order to control setting behavior, strength development, and volume stability. The ball mills used for finish grinding are similar to the mills used to grind the raw materials. They are equipped with air separators that remove the fine particles and return the coarse material to the mills for further grinding. The final cement is so fine that 90% or more passes through a sieve having 60 openings per square millimeter (40,000 openings per square inch). The cement is stored in large silos until ready for distribution. Cement is typically shipped in bulk by truck, train, or barge, although most plants also have equipment for bagging cement into bags typically weighing 42 kg (94 lb).

Table 3.1—Chemical compounds formed in the cement kiln

Name	Chemical formula	Shorthand notation*
Tricalcium silicate (alite)	$3CaO{\cdot}SiO_2$	C_3S
Dicalcium silicate (belite)	$2CaO{\cdot}SiO_2$	C_2S
Tricalcium aluminate	$3CaO{\cdot}Al_2O_3$	C_3A
Tetracalcium aluminoferrite (ferrite phase)	$4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$	C_4AF

*Shorthand notation routinely used by cement chemists using abbreviations for the oxides: $CaO = C$; $SiO_2 = S$; $Al_2O_3 = A$; $Fe_2O_3 = F$; $SO_3 = S$; and $H_2O = H$.

2.4—Quality control

The manufacture of portland cement involves complex chemical reactions, and all stages of production require close monitoring and control. Plant chemists analyze the raw materials from the quarry, the blending of materials, and the finished products using online automated analytical controls.

Cement is regularly sampled and tested by the producer. Tests include both chemical analysis and physical tests such as strength, fineness, and setting behavior. Tests on cement are done for quality control and to verify that the cement meets the requirements of standards such as ASTM C 150. The cement manufacturer is able to supply these data on request in the form of a mill-test report that serves as a manufacturer certification that the cement meets the requirements of the standard. Requests for this data should be made when required by the project specifications.

CHAPTER 3—PROPERTIES AND CHARACTERISTICS OF CEMENTS

3.1—Compound composition

As the raw materials are processed into portland cement, the chemical constituents of these materials combine at the high temperatures of the kiln to form new compound phases. Portland cement may be considered to consist of four primary chemical compounds (or phases), as listed in Table 3.1. These compounds are sometimes referred to by the chemical shorthand notation shown in parentheses.

3.2—Types of portland cement

The four main compounds, together with sources of calcium sulfate, may be present in different proportions and ground to different finenesses, resulting in slightly different chemical and physical properties for portland cements. Five principal types of portland cement are listed in ASTM C 150. The typical compound composition of these cements is given in Table 3.2. It can be seen that the sum of $C_3S + C_2S$ is approximately 75% by mass for each of the five types, so portland cements could be called calcium silicate-based cements.

ASTM C 150 is a combination prescriptive and performance-based specification for portland cement. That means the specification spells out the (maximum or minimum) chemical compound composition, like a recipe, while also having requirements for performance characteristics like strength and setting time.

Table 3.2—Typical compound composition of portland cement*

Cement type	ASTM C 150	C_3S	C_2S	C_3A	C_4AF	Fineness, m^2/kg
I	General purpose	55	19	10	7	370
II	Moderate sulfate resistance (and moderate heat of hydration as option)	51	24	6	11	370
III	High early strength	56	19	10	7	540
IV	Low heat of hydration	28	49	4	12	380
V	Sulfate-resistant	38	43	4	9	380

*From *Design and Control of Concrete Mixtures*, PCA Engineering Bulletin, 13th Edition, 1992. Reproduced by permission from the Portland Cement Association, Skokie, Ill.

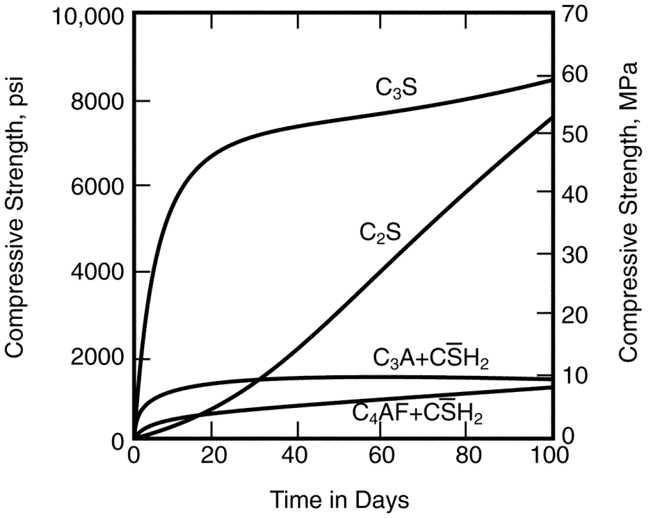


Fig. 3.1—Strength of cement compounds (From Design and Control of Concrete Mixtures*, PCA Engineering Bulletin, 13th Edition, 1992. Reproduced by permission from the Portland Cement Association, Skokie, Ill.)*

Though many manufacturers and specifiers still rely on ASTM C 150, other types of specifications, namely performance specifications, are also available. Rather than prescribe what the cement must contain, these specifications measure conformance through the cement's ability to meet certain physical test parameters such as strength, setting time, and expansion. Performance specifications are well suited to blended cements. They allow creative and efficient use of other resources, such as fly ash, blast-furnace slag, and other industrial by-products. ASTM has one performance specification for cement, ASTM C 1157. These cements are not classified as Types I through V, but follow letter designations.

3.3—Hydration of portland cements

The differences in composition of the five ASTM C 150 cement types are used to achieve the special properties desired. The properties of a hydraulic cement are determined, for the most part, by the way each cement compound reacts with water, a process known as hydration. Hydration causes portland cement (and hence the concrete made with it) to harden and develop strength. Figure 3.1 shows how each of the four compounds develop strength. It can be seen that C_3S gains most of the strength developed in the first 2 to 3 weeks. C_2S contributes to long-term strength, whereas C_3A and C_4AF primarily contribute to early strength gain.

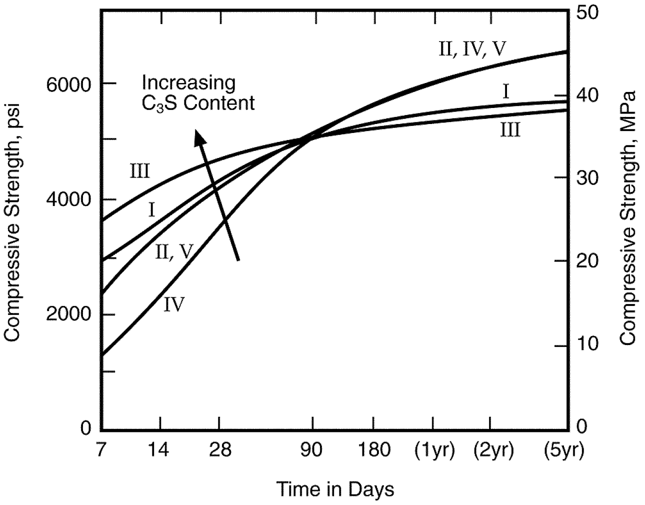


Fig. 3.2—Rates of strength development for concrete made with different cement types. (From Design and Control of Concrete Mixtures*, PCA Engineering Bulletin, 13th Edition, 1992. Reproduced by permission from the Portland Cement Association, Skokie, Ill.)*

Table 3.3—Characteristics of hydration of cement compounds

Compound	Reaction rate	Strength attained	Liberation of heat, cal/g at 7 days
C_3S	Moderate	High	High (1.10)
C_2S	Slow	Low at first, high later	Low (0.20)
C_3A	Fast	Low	Very high (1.95)
C_4AF	Moderate	Low	Moderate (0.50)

It can be seen in Fig. 3.2 that the early strength development of the five types of portland cement is approximately proportional to their C_3S content. The early strength development of Type III cement is generally due to its greater fineness. Long-term strengths are more nearly the same.

C_3A is much more reactive than C_3S and could, on occasion, lead to premature stiffening (flash set) when first mixed with water. Flash set was a problem with early portland cements, but it was found that the addition of gypsum (calcium sulfate) could be used to control setting behavior. The gypsum controls the setting characteristics of C_3A. When the C_3A hydration is properly controlled, setting of hydraulic cement is determined by the hydration behavior of C_3S. The period during which concrete remains workable is due to the fact that C_3S only starts to react rapidly after a few hours of contact with water. This is a fortunate occurrence since it allows for the handling and placing of concrete in the field.

The chemical reaction between cement and water, known as hydration, generates heat. This heat raises the temperature of the concrete. For large masses of concrete such as dams, large foundations, and large bridge abutments, it is necessary to control the rate of temperature rise in the structure to prevent cracking due to thermal stress. This can be accomplished by selecting a type of cement with low or moderate rate of heat generation, by the addition of chemical admixtures, pozzolans, and slags and through proper construction practices. The contribution of each compound to this temperature rise depends on the amount of heat it liberates and its rate of hydration. C_3A and C_3S hydration produce the most heat and hence contribute to most of the temperature rise in concrete during hydration. The temperature rise in concretes is shown in Fig. 3.3, and is approximately proportional to the sum of $C_3A + C_3S$.

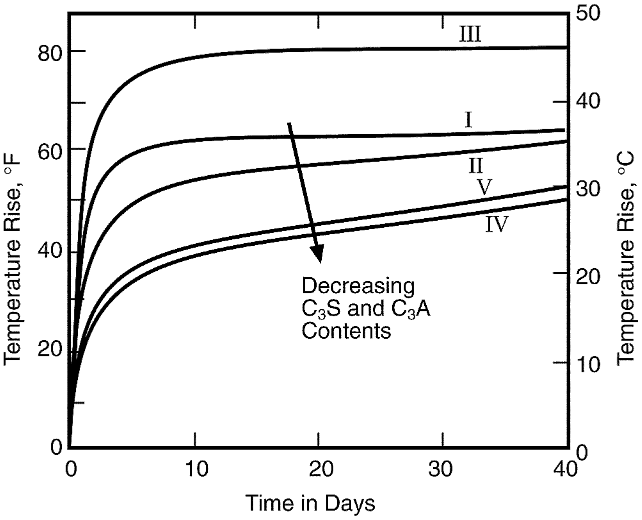


Fig. 3.3—Temperature rise in mass concrete made with different cement types. (From Design and Control of Concrete Mixtures*, PCA Engineering Bulletin, 13th Edition, 1992. Reproduced by permission from the Portland Cement Association, Skokie, Ill.)*

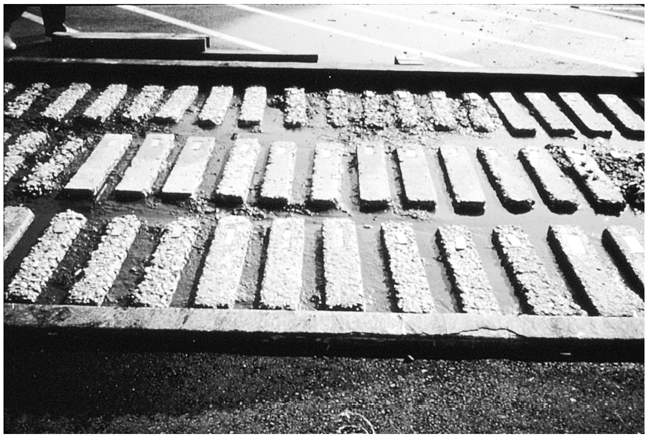


Fig. 3.4—Concrete beams after 7 years in sulfate-rich soil in Sacramento, Calif., test facility.

The behavior of the four compounds during hydration, and their contribution to concrete performance can be conveniently summarized as shown in Table 3.3. The gray color of portland cement depends a great deal on the amount of iron oxide (FeO_2) present in the cement. Iron acts as a fluxing agent and is added to the raw materials to aid in the pyroprocessing (burning) of the raw materials in the kiln. In general, the higher the iron content of the cement, the darker gray the cement will appear. White portland cement contains very little iron. See Section 4.1.3.1.

In addition to the behavior of the cement compounds, some of the minor constituents may play a significant role throughout the chemical hydration process. Since the reactions that involve compound formation seldom go to completion during the clinkering operation, there are usually small amounts (less than 1% by mass) of uncombined calcium oxide (CaO referred to as free lime) present in the cement. If present in a sufficiently large amount, the expansion of free lime during hydration can cause cracking and strength loss (unsoundness) in concrete due to internal expansions. Unsoundness in concrete may also result if there are excessive amounts or certain forms of magnesium oxide (MgO) in the cement. MgO occurs in most raw materials and, when present above about 2% by mass, will crystallize as free MgO, which may also expand during the hydration of the cement. The reaction of MgO takes place very slowly, and so unsoundness may only appear after many months, or even years. An autoclave soundness test is required in ASTM C 150 to detect cements with excessive amounts of uncombined lime (CaO) or MgO. Hydrated lime [$Ca(OH)_2$] and magnesium oxide (MgO) quenched in a glassy form will not expand.

Both sodium (Na) and potassium (K) (alkalis) are present in cement clinker in varying amounts up to about 1% by mass when expressed as equivalent sodium oxide (Na_2O eqv). The alkalis exist either as oxides dissolved in the major cement compounds, or separately as sulfates. The alkali sulfates act as accelerators: increasing early strength gain, but can marginally reduce strengths at later ages. Alkalis also may affect the performance of chemical admixtures in concrete.

Certain reactive siliceous or carbonate aggregates, which contain silica glass, opal, etc. may react with alkalis in cement to produce expansion of the concrete and cracking in the long term. This phenomenon is called alkali-aggregate reaction, or AAR.

Alkali-aggregate reaction depends on the reactive mineral in the aggregate and available alkalis. The common form of reaction is alkali-silica reaction (ASR), whereas a rare form is alkali-carbonate reaction (ACR). ASR has been studied frequently and accounts for most of the discussion here because it is the more common of the two. ASR forms a gel that is capable of absorbing water. As the gel takes up water, it expands, and can lead to cracking of the cement matrix and overall expansion of the concrete. When it is necessary to use aggregates that are potentially reactive, ASR can be controlled by using a pozzolanic addition such as fly ash, ground granulated blast-furnace slag (GGBFS), or a portland cement having low alkali content (less than 0.6% equivalent sodium oxide). These materials chemically combine with the alkalis to lower the available free alkalis that react with the aggregate.

Other minor constituents in hydraulic cement, totaling less than 1%, may include: titanium, phosphorous, manganese, and strontium. These materials appear to have little effect on the behavior of the cement. Titanium, manganese, and iron do, however, have an effect on cement color.

3.4—Cement fineness

The fineness of cement has a direct effect on the rate at which cement hydrates. Finer cements cause a more rapid generation of heat and greater strength gain, particularly during the early period of hydration. A coarser-ground cement (250 to 280 m^2/kg, Blaine) tends to produce lower early strength than conventionally ground cement (320 to 400 m^2/kg, Blaine) and may affect the workability and bleeding of the concrete. Higher fineness (exceeding 400 m^2/kg, Blaine) tends to increase early strength development and reduce bleeding. Type III cements are generally much more finely ground than other types, with fineness often exceeding 500 m^2/kg.

The fineness of cement has increased over the years primarily because of user demands for more rapid strength development in concrete. While cement fineness formerly averaged slightly more than 300 m^2/kg, Blaine for Type I in the 1950s, similar cements today average about 370 m^2/kg, Blaine. Concrete mixtures with high fineness ground cements will generally have a higher water demand for the required consistency and will bleed at a slower rate. Cements having fineness above 400 m^2/kg, Blaine, typically require higher dosages of air-entraining admixtures to achieve a given level of air entrainment in concrete.

3.5—Setting behavior

The setting characteristics of portland cement paste are defined by initial set and final set. Initial set indicates the approximate time at which the paste begins to stiffen considerably, while final set roughly indicates the time at which the paste has hardened and can support some load. These times of set are tested according to standardized procedures and have no special relationship to concrete setting behavior. Generally, initial set occurs within 1 to 4 h, and final set in 3 to 6 h. Setting times are affected by minor constituents in the cement such as alkalis and sulfates, by fineness, water-cement ratio, ambient temperature, and inclusion of mineral and chemical admixtures. Concretes generally set more slowly than cement paste because of the higher water-cement ratios. There are two types of abnormal setting behavior that should be mentioned:

(i) *False set.* This refers to the rapid setting that occurs without the liberation of much heat. Plasticity can be regained by further mixing without the need to add more water, and thus is not a problem where concrete is mixed for long periods (ready-mixed concrete). Increasing mixing time when possible will help to reduce a false set problem.

(ii) *Flash set (or quick set).* This behavior is accompanied by the liberation of considerable heat. The plasticity of the mixture cannot be regained with additional mixing or water.

3.6—Heat of hydration

Heat is liberated during the hydration reactions of the cement compounds. The amount of temperature rise in a concrete mass will depend on the cement content, the rate of hydration (determined by cement fineness, ambient temperature, and admixtures), the cement composition, the volume of aggregate, the thickness of the concrete member, and the rate at which heat is lost by the concrete to the surroundings. The

Table 3.4—Effect of sulfate concentration on attack of concrete

Degree of attack	Soluble sulfate in soils, %	Sulfate in water, ppm	Recommended cement
Mild	0.00 to 0.10	0 to 150	—
Moderate*	0.01 to 0.20	159 to 1500	II, IP†, or IS†
Severe	0.20 to 2.00	1500 to 10,000	V
Very severe	Over 2.00	Over 10,000	V + pozzolan or slag‡

Note: Adapted from "Guide to Durable Concrete (ACI 201.2R-92 [reapproved 1997])," American Concrete Institute, 1998.

*Seawater also falls into this category.

†Cements that satisfy conditions for moderate sulfate resistance; that is, IP(MS) and IS(MS).

‡Use a pozzolan or slag that has been determined by tests to improve sulfate resistance when used in concrete containing Type V cement.

Table 3.5—Types of cement required for concrete exposed to sulfates in soil or water

Degree of attack	Water soluble sulfate in soil, %	Sulfate in water, ppm	Cement	Water-cement ratio, maximum
Mild	0.00 to 0.10	0 to 150	—	—
Moderate*	0.01 to 0.20	150 to 1500	II, IP(MS), IS(MS)	0.50
Severe	0.20 to 2.00	1500 to 10,000	V	0.45
Very severe	Over 2.00	Over 10,000	V + pozzolan†	0.45

Note: Adapted from "Guide to Durable Concrete (ACI 201.2R-92 [reapproved 1997])," American Concrete Institute, 1998.

*Seawater.

†Use a pozzolan or slag that has been determined by tests to improve sulfate resistance when used in concrete Type V cement.

heat of hydration may cause considerable rise in concrete temperatures in the first few days of hydration, and temperature will continue to rise in mass concrete over longer periods. In cold weather, the heat of hydration may be utilized to help protect the concrete from freezing and increase the rate of hydration. Fly ash and other pozzolans or ground granulated blast-furnace slags can be used as a partial replacement for portland cement to control the heat gain of mixtures during hot weather or in mass concrete.

Cement composition and fineness affect the rate of heat generation. C_3A and C_3S are primarily responsible for high early heat generation. The rate of hydration will be faster as the fineness of the cement grind increases, although the total heat of hydration over a long time will not be particularly affected. Concrete proportions influence the amount of generated heat primarily as a result of cement content, with higher cement contents raising the heat of hydration.

3.7—Strength development

As shown in Fig. 3.2, the rate of early strength development depends on cement composition. Other factors that affect strength gain are cement fineness, use of supplementary cementitious materials, curing temperature, chemical or mineral admixtures, water-cement ratio, and curing conditions. The rate of early strength gain is directly correlated with the rate of hydration. The ultimate strength reached does depend to some extent on the initial rate of strength gain. The faster the early strength gain, the lower the ultimate strength, as can be seen in Fig. 3.2.

3.8—Sulfate resistance

Many concretes have been found to be susceptible to deterioration in soils, ground waters, or seawaters that contain high levels of sulfates. Sulfates react with the aluminum-containing phases of portland cement concrete-mortar-paste, causing internal expansion. It has been found that the resistance of a concrete to sulfate attack is related to the C_3A content of the cement and to the total amount of aluminate compounds, C_3A and C_4AF. Studies have shown that the ratio of water to total cementitious material is also a factor in sulfate resistance (Stark 1989). Type II cement is recommended for concrete that needs moderate sulfate resistance, and Type V cement or Type V cement plus a pozzolan is recommended for high sulfate resistance. These levels have been defined by ACI Committee 201 and are shown in Tables 3.4 and 3.5.

Seawater attack on concrete is generally thought to be of concern only in warm environments. Examinations of concrete in contact with cooler seawaters in San Francisco Bay and Puget Sound, however, reveal that concretes in cool environments are also attacked.

Seawater attack comes from components in salt water like sulfates and chlorides, as well as salt crystallization in concrete voids. Internal expansion then forces the concrete apart. Damage is usually most pronounced in the splash zone where concrete alternates between wet and dry conditions. Submerged portions and dry portions typically don't experience as much deterioration.

CHAPTER 4—PORTLAND CEMENTS AND THEIR SPECIFICATIONS

4.1—Cement types

Portland cement is most often manufactured to conform with ASTM Specification C 150, which designates five basic types: I, II, III, IV, and V. The chemical and physical requirements for portland cement given in ASTM C 150 are shown in Tables 4.1 and 4.2, respectively. The tests for these requirements are described in Chapter 5.

Type I is a general purpose cement suitable for all uses except where special properties of the other types are required. It is used in most types of construction; for example, pavements, bridges, reinforced concrete buildings, culverts, reservoirs, masonry units, and water pipes.

Type II is used where moderate sulfate resistance is required, for drainage and environmental structures in which sulfate concentration is higher than normal, or for concrete exposed to seawater. Type II can also be specified when moderate heat of hydration is desirable, as in mass concrete, dams, large piers, heavy retaining walls, and abutments. The lower heat of hydration option needs to be specified when cement is purchased. In some parts of the country, Type II serves as a general purpose cement. Some manufacturers produce a cement that meets both Type I and Type II requirements. These cements are known as Type I/II but there is no specific ASTM designation for Type I/II. Most cement manufactured in the U.S. meets Type I or Type II specifications.

Table 4.1—ASTM C 150 standard chemical requirements[*]

Cement type,[†] %	I and IA	II and IIA	III and IIIA	IV	V
Silicon dioxide (SiO_2), minimum	—	20.0[‡§]	—	—	—
Aluminum oxide (Al_2O_3), maximum	—	6.0	—	—	—
Ferric oxide (Fe_2O_3), maximum	—	6.0[‡§]	—	6.5	—
Magnesium oxide (MgO), maximum	6.0	6.0	6.0	6.0	6.0
Sulfur trioxide (SO_3),[‖] maximum, when C_3A[#] is 8% or less	3.0	3.0	3.5	2.3	2.3
Sulfur trioxide (SO_3),[‖] maximum, when C_3A[#] is more than 8%	3.5	N/A	4.5	N/A	N/A
Loss on ignition, maximum	3.0	3.0	3.0	2.5	3.0
Insoluble residue, maximum	0.75	0.75	0.75	0.75	0.75
Tricalcium silicate (C_3S),[#] maximum	—	—	—	35[‡]	—
Dicalcium silicate (C_2S),[#] minimum	—	—	—	40[‡]	—
Tricalcium aluminate (C_3A),[#] maximum	—	8	15	7[‡]	5[§]
Tetracalcium aluminoferrite plus twice the tricalcium aluminate[#] ($C_4AF + 2(C_3A)$), or solid solution ($C_4AF + C_2F$), as applicable, maximum	—	—	—	—	25[§]

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[†] See Note 1.

[‡] Does not apply when heat of hydration limit in Table 4 is specified.

[§] Does not apply when sulfate resistance limit in Table 4 is specified.

[‖] There are cases where optimum SO_3 (using Test Method C 563) for a particular cement is close to or in excess of the limit in this specification. In such cases where properties of a cement can be improved by exceeding the SO_3 limits stated in this table, it is permissible to exceed the values in the table, provided it has been demonstrated by Test Method C 1038 that the cement with the increased SO_3 will not develop expansion in water exceeding 0.020% at 14 days. When the manufacturer supplies cement under this provision, he shall, upon request, supply supporting data to the purchaser.

[#] All values calculated as described in this note shall be rounded according to Practice E 29. When evaluating conformance to a specification, round values to the same number of places as the corresponding table entry before making comparisons. The expressing of chemical limitations by means of calculated assumed compounds does not necessarily mean that the oxides are actually or entirely present as such compounds.
When expressing compounds, $C = CaO$; $S = SiO_2$; $A = Al_2O_3$; and $F = Fe_2O_3$. For example, $C_3A = 3CaO{\cdot}Al_2O_3$.
Titanium dioxide and phosphorous pentoxide (TiO_2 and P_2O_5) shall not be included with the Al_2O_3 content. See Note 2.
When the ratio of percentages of aluminum oxide to ferric oxide is 0.64 or more, the percentages of tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite shall be calculated from the chemical analysis as follows:
Tricalcium silicate = $(4.071 \times \%\ CaO) - (7.600 \times \%\ SiO_2) - (6.718 \times \%\ Al_2O_3) - (1.430 \times \%\ Fe_2O_3) - (2.852 \times \%\ SO_3)$
Dicalcium silicate = $(2.867 \times \%\ SiO_2) - (0.7544 \times \%\ C_3S)$
Tricalcium aluminate = $(2.650 \times \%\ Al_2O_3) - (1.692 \times \%\ Fe_2O_3)$
Tetracalcium aluminoferrite = $3.043 \times \%\ Fe_2O_3$
When the alumina-ferric oxide ratio is less than 0.64, a calcium aluminoferrite solid solution (expressed as $ss(C_4AF + C_2F)$) is formed. Contents of this solid solution and of tricalcium silicate shall be calculated by the following formulas:
$ss(C_4AF + C_2F) = (2.100 \times \%\ Al_2O_3) + (1.702 \times \%\ Fe_2O_3)$
Tricalcium silicate = $(4.071 \times \%\ CaO) - (7.600 \times \%\ SiO_2) - (4.479 \times \%\ Al_2O_3) - (2.859 \times \%\ Fe_2O_3) - (2.852 \times \%\ SO_3)$
No tricalcium aluminate will be present in cements of this composition. Dicalcium silicate shall be calculated as previously shown.

Type III is used when high early strength is desired. Examples are early removal of forms for cast-in-place concrete, precast concrete, and slipformed concrete. Under cold weather conditions, Type III is beneficial because of its faster rate of hydration, and hence faster rate of strength gain.

Type IV is used when the amount of heat of hydration must be minimized; for example, in massive structures such as gravity dams, where thermal cracking is likely to occur. Although concrete made with Type IV develops strength quite slowly, this is not a problem for such structures. Type IV is no longer made in the U.S. because other methods of controlling temperature are available. Two of these other methods include use of Type II cement with pozzolans and/or slags, and removing heat with coolants.

Type V should be used when high sulfate resistance is required, such as when concrete is exposed to severe sulfate attack as with soils or groundwaters having a high sulfate content. Type V develops strength at a slower rate than Type I cement and has a lower heat of hydration.

Air-entrained cements—ASTM C 150 also specifies air-entraining versions of Types I, II, and III, and designates them as Types IA, IIA, and IIIA, respectively. These cements are interground with an air-entraining agent at the cement manufacturing plant and may be used when air-entrained concrete is required. Air-entrained cements may not always be commercially available. When air-entrained cements are used, proper quality control of air contents should still be exercised at the job site. It is often easier to control entrained air content in concrete by using a non-air-entrained cement and a chemical air-entraining agent conforming to ASTM C 260.

Some highway departments and other specifying agencies further modify these specifications to meet their particular needs, the most well known being the American Association of State Highway and Transportation Officials (AASHTO) M-85, Standard Specification for Portland Cement. These are based on, and similar to, ASTM C 150 in chemical requirements and, in most instances, a particular cement satisfies all these specifications. The Canadian Standards Association (CSA) has developed similar standards for Canada.

4.1.1 *Blended cements*—Portland cement or clinker can be blended or interground with other materials to achieve certain properties. These cements are specified under ASTM Specification C 595 and C 1157. There are five classes of blended cement in C 595:

Table 4.2—ASTM C 150 standard physical requirements[*]

Cement type[†]	I	IA	II	IIA	III	IIIA	IV	V
Air content of mortar,[‡] volume %:								
Maximum	12	22	12	22	12	22	12	12
Minimum	—	16	—	16	—	16	—	—
Fineness,[§] specific surface, m^2/kg (alternative methods):								
Turbidimeter test, minimum	160	160	160	160	—	—	160	160
Air-permeability test, minimum	280	280	280	280	—	—	280	280
Autoclave expansion, maximum, %	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Strength, not less than values shown for ages indicated as follows [compressive strength, MPa (psi)]:[‖]								
1 day	—	—	—	—	12.0 (1740)	10.0 (1450)	—	—
3 days	12.0 (1740)	10.0 (1450)	10.0 (1450) 7.0[#] (1020)[#]	8.0 (1160) 6.0[#] (870)[#]	24.0 (3480)	19.0 (2760)	—	8.0 (1160)
7 days	19.0 (2760)	16.0 (2320)	17.0 (2470) 12.0[#] (1740)[#]	14.0 (2030) 9.0[#] (1310)[#]	—	—	7.0 (1020)	15.0 (2180)
28 days	—	—	—	—	—	—	17.0 (2470)	21.0 (3050)
Time of setting, Gilmore test (alternative methods):[**]								
Initial set, minimum, not less than	60	60	60	60	60	60	60	60
Final set, minimum, not more than	600	600	600	600	600	600	600	600
Time of setting, Vicat test[††] (alternative methods):[**]								
Time of setting, minimum, not less than	45	45	45	45	45	45	45	45
Time of setting, minimum, not more than	375	375	375	375	375	375	375	375

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[†] See Note 1.

[‡] Compliance with requirements of this specification does not necessarily ensure that desired air content will be obtained in concrete.

[§] Testing laboratory shall select fineness method to be used. When sample fails to meet requirements of air-permeability test, however, the turbidimeter test shall be used, and requirements in this table for turbidmetric method shall govern.

[‖] Strength at any specified test age shall be not less than that attained at any previous specified test age.

[#] When optional heat of hydration or chemical limit on sum of tricalcium silicate and tricalcium aluminate is specified.

[**] Time-of-setting test required shall be specified by purchaser. In case he does not so specify, requirements of Vicat test only shall govern.

[††] Time of setting is that described as initial setting time in Test Method C 191.

- Portland blast-furnace slag cement (Type IS);
- Portland-pozzolan cement (Type IP and Type P);
- Pozzolan-modified portland cement (Type I (PM));
- Slag cement (Type S); and
- Slag-modified portland (Type I (SM)).

Although blended cements are common in European countries, they have not been used as extensively in the U.S., but are gaining popularity because they require less energy to manufacture, they can be made with by-product materials that would normally be disposed in a landfill, thus reducing solid waste, and offer performance benefits for certain applications. Special requirements of these blended cements are given in Tables 4.3 and 4.4.

4.1.1.1 *Portland blast-furnace slag cement*—Portland blast-furnace slag cement is a blend of portland cement (usually Type I or II) and 25 to 70% by mass (weight) granulated (quenched) blast-furnace slag. There are two basic types: IS and IS-A (air entrained). Such cement may be used for general concrete construction when the specific properties of other types are not required. When moderate sulfate resistance or moderate heat of hydration is specified, the suffixes (MS), or (MH), or both, respectively, may be added; therefore, a cement which is air-entraining and moderately sulfate resistant would be designated Type IS-A (MS).

4.1.1.2 *Slag cement*—ASTM C 595 also specifies slag cement, designated either Type S or S-A, which are blends of a minimum of 70% water-quenched, blast-furnace slag and portland cement or hydrated lime. Therefore, they are not portland cements and should be called slag cements. These cements are used mainly for large hydraulic structures such as dams and bridge piers and also are blended with portland cement for producing concrete or blended with hydrated lime for producing masonry cement. Such cements develop strength very slowly (see Table 4.4).

4.1.1.3 *Slag-modified portland cement*—Specifications for slag-modified portland cements, Types I (SM) and I (SM)-A, allow up to 25% slag additions by mass. In producing these cements, granulated blast-furnace slag is either interground with the portland cement clinker, or itself finely ground and subsequently blended with finished cement. The designation for slag-modified portland cement is Type I (SM) and it is used for general construction. Supplemental designations include air entrainment, moderate sulfate resistance, or moderate heat of hydration.

Table 4.3—Compositional requirements of blended cements (ASTM C 595)[*]

Cement type, %	I(SM), I(SM)-A, IS, IS-A	S, SA	I(PM), I(PM)-A, P, PA, IP, IP-A
Magnesium oxide (MgO), maximum,	—	—	6.0
Sulfur reported as sulfate (SO_3), maximum[†]	3.0	4.0	4.0
Sulfide sulfur (S), maximum	2.0	2.0	—
Insoluble residue, maximum	1.0	1.0	—
Loss on ignition, maximum	3.0	4.0	5.0
Water-soluble alkali, maximum	—	0.03[‡]	—

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[†] When it has been demonstrated by Test Method C 563 that optimum SO_3 exceeds a value of 0.5% less than specification limit, an additional amount of SO_3 is permissible provided that, when cement with additional calcium sulfate is tested by Test Method C 265, calcium sulfate in hydrated mortar at 24 ± 1/4 h, expressed as SO_3, does not exceed 0.50 g/L. When manufacturer supplies cement under this provision, he will, upon request, supply supporting data to purchaser.

[‡] Applicable only when cement is specified to be nonstaining to limestone. Amount and nature of staining material in limestone vary with stone. Alkali in any cement may, therefore, induce markedly different staining on different stone, even though stone may have come apparently from same source. Amount of alkali permitted by specification should not cause stain unless stone high in staining material has been used, or unless insufficient means have been used to prevent infiltration of water into masonry.

Table 4.4—Physical requirements of blended cements (ASTM C 595)[*]

Cement type	I(SM), IS, I(PM), IP	I(SM)-A, IS-A, I(PM)-A, IP-A	IS(MS), IP(MS)	IS-A(MS), IP-A(MS)	S	SA
Fineness	†	†	†	†	†	†
Autoclave expansion, maximum, %	0.80	0.80	0.80	0.80	0.80	0.80
Autoclave contraction, maximum, %[‡]	0.20	0.20	0.20	0.20	0.20	0.20
Time of setting, Vicat test:[§]						
Set, minutes, not less than	45	45	45	45	45	45
Set, h, not more than	7	7	7	7	7	7
Air content of mortar (Test Method C 185), volume %	12 maximum	19 ± 3	12 maximum	19 ± 3	12 maximum	19 ± 3
Compressive strength, minimum, MPa (psi):						
3 days	13.0 (1890)	10.0 (1450)	11.0 (1600)	9.0 (1310)	—	—
7 days	20.0 (2900)	16.0 (2320)	18.0 (2610)	14.0 (2030)	5.0 (720)	4.0 (580)
28 days	25.0 (3620)	20.0 (2900)	25.0 (3620)	20.0 (2900)	11.0 (1600)	9.0 (1310)
Heat of hydration:[‖]						
7 days, maximum, kj/kg (cal/g)	290 (70)	290 (70)	290 (70)	290 (70)	—	—
28 days, maximum, kj/kg (cal/g)	330 (80)	330 (80)	330 (80)	330 (80)	—	—
Water requirement, maximum weight % of cement	—	—	—	—	—	—
Drying shrinkage, maximum, %	—	—	—	—	—	—
Mortar expansion:[#]						
At age of 14 days, maximum, %	0.020	0.020	0.020	0.020	0.020	0.020
At age of 8 weeks, maximum, %	0.060	0.060	0.060	0.060	0.060	0.060
Sulfate resistance expansion at 180 days, maximum, %	(0.10)[**]	(0.10)[**]	0.10	0.10	—	—

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[†] Both amount retained when wet sieved on 45 μm (No. 325) sieve and specific surface by air permeability apparatus, m^2/kg, shall be reported on all mill test reports requested under 14.4.

[‡] Specimens shall remain firm and hard and show no signs of distortion, cracking, checking, pitting, or disintegration when subjected to autoclave expansion test.

[§] Time of setting refers to initial setting time in Test Method C 191. Time of setting of cements containing a user-requested accelerating or retarding functional addition need not meet limits of this table, but shall be stated by manufacturer.

[‖] Applicable only when moderate (MH) or low (LH) heat of hydration is specified, in which case the strength requirements shall be 80% of values shown in table.

[#] Test for mortar expansion is an optional requirement to be applied only at purchaser's request and should not be requested unless cement will be used with alkali-reactive aggregate.

[**] Optional sulfate resistance criterion that applies only if specifically invoked.

4.1.1.4 *Portland-pozzolan cement*—Portland-pozzolan cement includes four types: IP, IP-A, P, and P-A, which must meet the requirements of ASTM C 595 (Tables 4.3 and 4.4). The first two types may be used for general concrete construction, and the latter two when high strength at an early age is not required. The letter "A" designates the air-entraining counterparts. These cements are produced by either intergrinding portland cement clinker and pozzolan, by blending portland cement and finely divided pozzolan, or by a combination of both intergrinding and blending. Portland-pozzolan cements contain between 15 and 40% pozzolan in the blended cement. In addition, the cements may be designated low or moderate heat of hydration (LH or MH), as well as moderate sulfate resistant (MS) for Types IP and IP-A.

4.1.1.5 *Pozzolan-modified portland cement*—Pozzolan-modified portland cement is used for general construction. Type I (PM) cement is a combination of portland cement or portland blast-furnace slag cement and a fine pozzolan. The pozzolan is less than 15% by mass of finished cement (and if slag is used, it ranges from 25 to 70% by mass). Supplemental designations include air entrainment, moderate sulfate resistance, and moderate heat of hydration.

4.1.2 *Expansive cement*—ASTM C 845 covers the specification for expansive cement, a hydraulic cement that expands during the early hardening period after setting. The specification identifies three types of expansive cements: K, M, and S, with different expansive ingredients. Type K cement contains anhydrous calcium aluminosulfate (C_4A_3S), calcium sulfate, and uncombined lime; Type M cement contains a calcium aluminate cement and calcium sulfate; while Type S cement has higher-than-normal quantities of tricalcium aluminate (C_3A) and calcium sulfate. Expansion is caused by the hydration of these materials. The three types (K, M, and S) are suitable for use in shrinkage-compensating concrete. Essentially, these cements are designed to expand during hydration, and this expansion minimizes cracking caused by the subsequent shrinkage of the cement matrix that occurs on drying. For crack control, the expansion must be restrained by the reinforcing steel to induce a slight compressive stress in the concrete which then offsets the tensile stresses during shrinkage and inhibits cracking as discussed in ACI 223.

Expansive cements have been used for concrete structures where normal control joints to accommodate drying-shrinkage cracking are undesirable, for example, floors and slabs. Proper pre-job planning and on-site supervision, accompanied by good quality control throughout construction, are essential elements to a successful job. If adequate moist curing is not maintained, the desired expansion will not occur. Expansive cements should not be used in concrete subjected to sulfate attack unless prior testing indicates satisfactory resistance to the levels of attack expected in service.

4.1.3 *Other special cements*—In addition to the cements described above, there are several cements available for special applications, not all of which are covered by ASTM specifications. It should be emphasized that these cements are not used in general concrete work, but they may occasionally be encountered. Therefore, the more common classes are described below.

4.1.3.1 *White cement*—White cement is a portland cement made with similar raw materials, but the amount of iron oxide is kept low. White cement should conform to ASTM C 150 and is used mainly for architectural purposes; for example, in the fabrication of precast panels, stucco, terrazzo surfaces, and decorative concrete. White cement is often recommended for use in colored concrete or mortar. The plastic and hardened properties of concrete made with white cement should be verified by trial batches prior to starting a project.

4.1.3.2 *Water-repellent cement*—The addition of certain chemicals to regular portland cements can impart some water repellency to concrete. Water-repellent cement (sometimes incorrectly called waterproof cement) is commonly used for the construction of walls or other structures that are subjected to hydrostatic pressure, or used to resist the penetration of water or other liquids in basement walls and containment vessels. Agents intended to provide water-repellency are frequently affected adversely by cement alkalis. Water-repellent cements will not completely prevent water seepage under hydrostatic pressure. In addition, water repellents are more effective in concrete that is of high quality. There is no ASTM test for water repellency of cements.

4.1.3.3 *Masonry cement*—ASTM C 91 gives requirements for masonry cements. These are mixtures of portland cement, air-entraining agents, and finely divided material, such as ground limestone, hydrated lime, ground shale, or fly ash that are selected to improve the board life and workability of the fresh mortar and water impermeability of the hardened mortar. Considering that each of these additions has different material characteristics, uniformity of product properties must be carefully maintained by the cement producer. These cements are strictly controlled, offering potentially more consistent mortar to contractors (better color control, and uniformity).

4.1.3.4 *Mortar cement*—Mortar cement is a relatively new product designed for use in structural masonry applications. It is a hydraulic cement primarily used to produce masonry mortar. It is a prepackaged product that is mixed with sand and water at the job site to produce mortar. Mortar cement has lower maximum air content limits than masonry cement and has minimum bond strength requirements, as measured by ASTM test method C 1072. In seismic regions, mortar cement is accepted for use in structural masonry. In unreinforced structural masonry, higher allowable flexural tensile stress values apply for mortar cement or portland cement-lime mortars than for masonry cement mortars. ASTM C 1329 provides requirements for mortar cement.

4.1.3.5 *Oil well cement*—Oil well cements are manufactured in accordance with the American Petroleum Institute Specification APR Standard 10A. Cements are designated by eight classes. The classification for each is based on the pressure-temperature thickening-time encountered at specified depths in the primary cementing of casing in wells. Cement slurries may often be exposed to bottom-hole pressures in excess of 140 MPa (20,000 psi) and temperatures approaching 120 C (250 F). Oil well cements are made from the same basic ingredients as regular cements; however, certain properties are altered so that the cements can perform as intended at the higher temperatures and pressures encountered in deep wells. Admixtures and other ingredients such as sand, bentonite, pozzolan, and diatomaceous earth, are incorporated into the mixture for the purpose of controlling its fluid properties; organic compounds are added to control its setting time.

4.1.3.6 *Plastic cement*—Plastic cement is most commonly available in the Southwest and on the West Coast of the U.S. and complies to specifications set forth in ASTM C 1328. It is also classified in the UBC under 25-1. Plastic cement is a hydraulic cement used primarily for stucco and portland cement-based plastering construction. It consists of a mixture of portland and blended hydraulic cement, plasticizing materials (limestone, hydrated, or hydraulic lime), and other materials that enhance

Table 4.5—ASTM C 1157 standard physical requirements[*]

Cement type	GU	HE	MS	HS	MH	LH
Fineness	†	†	†	†	†	†
Autoclave length change, maximum, %	0.80	0.80	0.80	0.80	0.80	0.80
Time of setting, Vicat test:[‡]						
Initial, not less than, minimum	45	45	45	45	45	45
Initial, not more than, minimum	420	420	420	420	420	420
Air content of mortar volume, %	§	§	§	§	§	§
Strength range:[‖]						
1 day	—	10	—	—	—	—
3 days	10	17	10	5	5	—
7 days	17	—	17	10	10	5
28 days	—	—	—	17	—	17
Heat of hydration:						
7 days, maximum, kj/kg (kcal/kg); 28 days, maximum, kj/kg (kcal/kg)	—	—	—	—	290 (70)	250 (60) 290 (70)
Mortar bar expansion:						
14 days, % maximum	0.020	0.020	0.020	0.020	0.020	0.020
Sulfate expansion (sulfate resistance):[#]						
6 months, maximum, % (1 year, maximum, %)	—	—	0.10	0.050 (1.0)	—	—
Option R—low reactivity with alkali-reactive aggregates:[**]						
Expansion: 14 days, maximum % (56 days, maximum, %)	0.020 (0.060)	0.020 (0.060)	0.020 (0.060)	0.020 (0.060)	0.020 (0.060)	0.020 (0.060)
Optional physical requirements:						
Early stiffening, final penetration, minimum, %	50	50	50	50	50	50
Compressive strength,[**] minimum, MPa (psi), 28 days	28.0 (4060)	—	28.0 (4060)	—	22.0 (3190)	—

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[†] Both amount retained when wet sieved on 45 μm (No. 325) sieve and specific surface area by air permeability apparatus in m2/kg shall be reported on all certificates of test results requested from manufacturer.

[‡] Time of setting refers to initial setting time in Test Method C 191.

[§] Air content shall be reported on all certificates of test results requested from manufacturer. A given value in mortar does not necessarily assure that desired air content will be obtained in concrete.

[‖] Lowest strength range whose minimum shall apply at specified age unless a higher strength range is specified by purchaser. See Table 2 for applicable strength limits.

[#] In testing of HS cement, testing at 1 year shall not be required when cement meets 6-month limit. An HS cement failing 6-month limit shall not be rejected unless it also fails 1-year limit.

[**] Compliance with this requirement should not be requested unless cement will be used with alkali-reactive aggregate.

[††] When 28-day strengths are specified, sufficient time must be allowed for completion of the test. When required on certificate of test results, special arrangements for storage of cement pending completion of test may be required.

Table 4.6—ASTM C 1157 strength range limits[*]

Strength range	5	10	17	25	35	45
Compressive strength, minimum, MPa (psi)	5 (725)	10 (1450)	17 (2465)	25 (3625)	35 (5075)	45 (6525)
Compressive strength, maximum, MPa (psi)	15 (2175)	20 (2900)	30 (4350)	40 (5800)	60 (8700)	—

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setting, workability, water retention, or durability. Plastic cement must meet physical requirements for fineness, autoclave expansion, time of set, compressive strength, air content of mortar, and water retention. When plastic cement is used, no other plasticizers or lime may be added during mixing.

4.1.3.7 *Rapid setting cements*—Some concrete applications, such as repair and fast-track pavement construction, require concrete with high initial rates of strength gain. A number of techniques have proven successful in providing specified strengths in 4 hours or less. These techniques include high portland cement contents, Type III portland cement, low water-cement ratio, accelerating admixtures, and higher curing temperatures. Attempts to achieve more rapid strength gain have resulted in the development of a number of fast-setting hydraulic cement products.

Regulated-set cement is a calcium fluoroaluminate hydraulic cement formulated to produce concrete with setting times from a few minutes to an hour accompanied by rapid early strength development. These cement products are portland cement-based with functional additions that provide the accelerated set and strength gain.

Rapid hardening cements are used in construction applications such as pavement patching and fast-track paving, where load carrying strength must be developed in less than 4 h to allow for early opening of the roadway. These hydraulic cements are typically calcium sulfoaluminate combinations.

Another fast-setting cement is calcium aluminate based. This type of cement is capable of attaining design strengths in 1 day. It has been used in applications requiring chemical-resistant concrete or high corrosion resistance. Calcium aluminate can develop an unstable paste structure that results in loss of strength over time. For this reason, calcium aluminate cements should not be used in structural applications.

Fast-setting hydraulic cements, when available, are generally more expensive than ordinary portland cement. Because of their rapid setting characteristics, concrete containing these cement products is often more difficult to control at the job site, and is prone to cracking.

4.2—Performance specification for portland cements

In 1992, ASTM C 1157, a performance-based specification for blended cements in the U.S., was issued. It was revised in 1997 and now covers both portland and blended cements. This specification has primarily performance requirements as measured by standard cement and concrete tests and does not put restrictions on requirements on the cement composition. There are six designated types of cement: GU for general construction; HE for high-early strength; MS for moderates sulfate resistance; HS for high sulfate resistance; LH for low heat of hydration; and MH for moderate heat of hydration. Several job and concrete specifications permit the use of cements conforming to ASTM C 1157. The ASTM C 1157 requirements are shown in Tables 4.5 and 4.6.

CHAPTER 5—STANDARD TESTS FOR PORTLAND CEMENTS

The production of portland cement requires strict quality control to comply with established specifications for chemical and physical requirements. Over the years, a number of standard tests have been developed that can be carried out relatively easily and rapidly to ensure that the cement conforms to the desired standard. In the U.S., testing standards developed by ASTM are used to determine if the cement complies with specifications. Similar tests are used in Canada for evaluating conformance to CSA standards. It should be noted that these tests do not measure concrete behavior in the field. A cement passing these standards should be evaluated in concrete with local materials to ensure that the desired fresh and hardened concrete properties are obtained.

5.1—Chemical tests

Chemical analysis of portland cements is covered by ASTM C 114. This standard provides for referee, optional, and rapid techniques for measuring a variety of elements or compounds that can be found in cement. The referee method is used primarily to resolve disputes where chemical test results are being questioned, as in the case of two laboratories testing the same cement with the same methods but obtaining different results. No rejections of cement failing to meet chemical requirements may be made until the test is conducted using the referee method. Optional and rapid test methods are provided for those who need shorter or more convenient methods for routine testing.

Laboratories involved in testing cement generally verify their testing procedures and results by testing standard cement samples, and they participate in reference sample testing programs conducted by the Cement and Concrete Reference Laboratory (CCRL) at the National Institute of Standards and Technology (NIST). CCRL also conducts regular inspections of cement testing laboratories to insure that equipment and testing techniques comply with current ASTM methods. In addition, CCRL conducts a semiannual survey wherein approximately 400 laboratories test two samples of cement for interlaboratory comparison on all characteristics. This program enables a laboratory to statistically compare their results with averages from other laboratories.

Wet chemistry was for many years the primary technique of chemical analysis, although today instrumental analysis with atomic adsorption and x-ray fluorescence is being more widely used. Chemical analysis, either by wet chemistry or instrumental analysis, is used to determine the oxide composition (CaO, SiO_2, etc.) of cements. By using the formulas contained in the footnotes of ASTM C 150, the potential compound composition of the cement is calculated. The value of chemical test results is of importance to the user in determining which type of cement to use, as in the case of heat of hydration or sulfate resistance. Chemistry alone cannot be used to predict performance in concrete, and the cement producer will normally vary both chemical and physical characteristics to obtain the required performance characteristics for the cement. As an example, early age strength is affected by fineness as well as chemistry.

Two other chemical characteristics of interest are loss on ignition and insoluble residue. Loss on ignition is an indication of prehydration of the cement that can occur during storage of clinker at the cement plant. High ignition loss can potentially reduce strengths. Insoluble residue is a means of detecting contamination that can occur at a cement plant or when storing clinker. ASTM C 150 limits insoluble residue to less than 0.75%.

5.2—Physical tests

ASTM requirements for physical tests include air content, fineness, soundness, time of set, false set, heat of hydration, sulfate expansion, and strength. Physical tests are more aligned to the characteristics of concrete.

5.2.1 *Fineness*—Fineness is described by a single parameter, the specific surface area, determined by one of two standard-used methods. Because cement particles are irregularly shaped, and the different methods measure specific surface area by different techniques, the measurement of fineness by one method will not have the same numerical value as the other. Whenever fineness is reported, the method used to measure it must also be identified. The real use of any given method is to allow a relative comparison between cement from the same source and different cements. Two methods of determining the fineness of cement are recognized by ASTM: the turbidimeter test (Wagner) and the air permeability test (Blaine).

Wagner turbidimeter (ASTM C 115)—The Wagner turbidimeter method of measuring fineness involves a suspension of cement in kerosene through which light is passed. The cross-sectional area of the particles intersecting the beam can be determined by measuring the light intensity. From these data, specific surface area and a particle size distribution can be obtained.

Blaine air permeability (ASTM C 204)—The air permeability method of determining fineness is based on measuring the time required to pass a given volume of air through a porous bed of cement. The time is compared with the time for a standard cement sample issued by NIST, which has a known specific surface area. The specific surface area of the unknown sample can then be calculated, since it is proportional to the square root of the time.

Both the Wagner and Blaine methods provide an acceptable way of determining relative fineness. The Blaine numerical value is generally about 1.8 times the Wagner value because of the different theories involved. The Blaine method is more commonly used, but in cases of dispute, the Wagner method is deemed to govern.

Fineness was originally specified as a minimum value to insure strength development and to minimize bleeding in concrete. Today we find that the majority of cements manufactured in the U.S. exceed the minimum ASTM limits for fineness. The trend has been toward more finely ground cements because they produce higher strengths at early ages. This is due to the fact that finer cements have a higher surface area exposed to water and hence a greater rate of hydration in the first few days. AASHTO M 85, however, places a maximum limit on cement fineness for some types to control water requirements and drying shrinkage of concrete.

5.2.2 *Setting behavior*—There are two commonly accepted test methods for determining the setting time of cement. They are both carried out on cement paste samples prepared by standard methods. Setting times determined by the two different methods will have different numerical values and the method used should be indicated when reporting setting times.

Setting time by the Vicat Needle (ASTM C 191) is measured on a standard molded specimen with a depth of 30 mm using a 1 mm diameter needle weighing 300 g. At regular intervals the needle is placed on the specimen surface and allowed to settle for 30 seconds. The elapsed time between mixing the cement and water and the time when the weighted needle penetrates 25 mm is the initial setting time. When no penetration is observed, the elapsed time from molding to that point is the final setting time. There is no final setting time requirement in ASTM C 150 when testing by the Vicat method.

Gillmore Needle (ASTM C 266) uses a standard specimen called a pat and measures initial set by penetration of a 2 mm diameter needle weighing 113 g and final set by penetration of a 1 mm diameter needle weighing 454 g. In each case, the setting time is that measured time when the needle will not make an appreciable indentation in the surface of the pat specimen.

These tests are used to determine if a cement sets according to the time limits specified by ASTM C 150 and other standards. The purpose of these limits is to help to insure that the user will have sufficient time to place and finish concrete after mixing. The final set limits are used to insure that the cement is setting in a normal fashion that will result in normal early strength gain.

5.2.3 *False set*—The test for abnormal early stiffening is described in ASTM C 451 (paste method), using the Vicat apparatus. This test is used to determine whether the cement complies with the optional requirements of ASTM C 150 when these are specified. It provides information as to whether the cement is likely to exhibit false set and make handling and placing the concrete difficult. False set is generally not a problem with transit mixing, where the concrete is continuously agitated before placing, or where the concrete is remixed prior to placement. The consequences of flash set are more severe, with complete loss of workability which cannot be regained. Another often-used test for false set is ASTM C 359 (mortar method). This test method uses a mortar mixture and measures stiffness of the mortar at specified time intervals followed by remixing and remeasuring. A false-setting mortar will develop early stiffness that will return to the original consistency after remixing.

5.2.4 *Soundness*—Soundness in cement paste is the absence of excessive volume change after setting. Unsoundness can result from the hydration of MgO (magnesium oxide) or CaO (free lime). Since some of the reactions are very slow, unsoundness may take months to develop. Thus, it is necessary to use some form of accelerated test so that tendencies toward unsoundness can be detected as a quality control measure during manufacture. The autoclave expansion tests (ASTM C 151) are designed to detect unsoundness due to both CaO and crystalline MgO. This method measures expansion of a standard mortar bar after it has been subjected to accelerated curing with steam at elevated temperature and pressure. Cement standards require expansion must be less than 0.80% of the original length. This is an accelerated test that clearly does not simulate service conditions, although it will detect an unsound cement that would cause concrete to crack. It does provide a valuable quality control measure, since changes in the expansion test results would indicate some irregularity in the cement manufacturing process.

5.2.5 *Heat of hydration*—The heat of hydration varies greatly with the cement composition, fineness, and concrete proportions, with C_3A and C_3S being primarily responsible for high heat evolution. Fineness of grinding also has an effect on the rate of heat evolution. Finely ground cements increase the hydration rate, but the total heat of hydration over a long time is not particularly affected. The heat of hydration may be defined as the amount of heat liberated (in cal/g of unhydrated cement) during the setting and hardening of portland cement at a given temperature. This is measured by the test method specified in ASTM C 186. Only Type II and Type IV cements have optional heat-of-hydration requirements in ASTM C 150, but AASHTO M 85 also has a limit for Type V cements.

Heat of hydration is particularly important in any massive concrete placement, such as gravity dams, mass foundations, and relatively thick concrete sections with high cement content mixtures (some high-performance and high-strength concretes). As cement hydrates, it gives off heat, but in most cases the heat is dissipated without detrimental effects. In mass concrete or thick sections, however, heat dissipation is restricted and internal temperatures can exceed exterior temperatures to the extent of developing thermal stresses sufficient to crack the concrete upon cooling. Numerous methods are available to alleviate potential problems arising from heat gain: partial replacement of cement with a pozzolan or slag, use of a cement meeting the low heat-of-hydration option of ASTM C 150 (Type IV is rarely available), control of concrete temperature, or cooling of the concrete mixture or structure.

5.2.6 *Strength tests*—Since concrete is used primarily in load-bearing applications, it follows that cement strength properties are of significant importance. A number of strength tests using mortars have been developed in order to answer two questions:

1. What are the strength characteristics of a particular cement?
2. How do different types of cement compare with one another?

The test for compressive strength prescribed in ASTM C 109 uses a 50 mm (2 in.) mortar cube as the test specimen. The sand-cement ratio is 2.75:1, using a standard sand, while the water-cement ratio (*w/c*) is 0.485 for all portland cements, and 0.460 for air-entraining portland cements. The specimens are moist-cured until they are tested. Mortars for blended cements in ASTM C 595 and C1157 are mixed with variable *w/c* to a constant flow—a measure of consistency.

Since cement strength increases with time, it is also necessary to specify the age at which tests should be carried out. Normally, minimum strengths are specified for 3, 7, and 28 days. In addition, high-early-strength cement (Type III) has a 1-day requirement. A point to remember is that the rate of strength gain is as important as the strength at a given age. Cement strength is only measured in compression. (Flexural or tensile strength is not specified in ASTM C 150 or other cement standards, although standard ASTM tests for these strengths in concrete are still recognized.)

It is important to note that the strengths of mortar as determined by these tests cannot be related directly to the strengths of concrete made with the same cements. Only a general relationship exists. Thus, the strength tests on mortars serve primarily as quality control tests in cement manufacturing to determine compliance with specifications and as an aid for comparing cements from different sources. The strength of concrete can only be determined from tests done on the concrete itself. The measurement of strength of cement mortar cubes is to insure compliance with standards. In practice, however, most cement sold in the U.S. exceeds ASTM C 150 strength limits by a wide margin. Normally the level of strengths in a geographic area is controlled by the market demands and limitations of raw materials. The user should also be concerned with how much the strength level varies. A mill test report represents the average properties from a defined production period of cement resulting in average values and has the prime objective of showing that the cement meets the strength requirements of the cement standard.

5.2.7 *Air content of mortar*—ASTM C 185 is used to determine the air content of a cement mortar. For cement without air-entraining additions, the purpose is to insure that the cement will not entrain undesired air; for air-entraining cement, the purpose is to insure that the additions are present in the correct quantity. ASTM C 150 specifies maximum and minimum air contents of the mortar for both air-entrained and nonair-entrained cements

In the test of air content of mortar (ASTM C 185), mortar is made with cement, a standard sand, and enough water for a required consistency. The mortar is placed in a standard container and the weight of mortar determined. The air content is calculated from the measured density and the calculated density of the air-free mixture. The calculated air-free density is determined from the mixture proportions and the separate densities of the constituents. Measuring air content of mortar should result in values of less than 12% for non-air-entraining cements, and 16 to 22% for air-entraining cements. The air content of air-entrained concrete is typically in the range of 5 to 8% and does not relate to this test of cement mortar.

5.2.8 *Sulfate expansion*—ASTM C 452 can provide useful information relating to sulfate resistance and is an optional requirement for Type V cements. This test measures the expansion of mortar bars made from a mixture of cement and gypsum such that the total SO_3 content is 7.0% by mass. After casting, the specimens are stored in water at 23 C (73 F), and the length determined at different times. The expansion is then a measure of the sulfate resistance of the cement and should not exceed 0.045% after 14 days. This test is seldom used in purchase specifications, since the values obtained may not correlate with sulfate expansions measured in concrete using the same cement. However, it is useful as a warning to prompt further investigations.

CHAPTER 6—FLY ASH AND OTHER POZZOLANS

The mineral admixtures of today were among the chief cementitious components of concretes produced many centuries ago. Commonly termed "pozzolans," these materials are capable of forming a durable binder. A pozzolan is defined in ASTM C 618 as "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties." These characteristics make pozzolans ideal additions to portland cement concrete mixtures. They are composed of similar materials and react with the products of hydrating cement to create additional cementitious binder. Pozzolanic material can be used to modify and improve plastic and hardened properties of concrete.

6.1—Classification of pozzolans

ASTM C 618 outlines the physical and chemical requirements of pozzolanic materials. Pozzolanic materials include natural pozzolans (Class N) and by-product materials. Natural pozzolans are notably volcanic ashes, diatomaceous earth, calcined clay, metakaolin clay, and rice hull ash. By-product material is most typically fly ash, classified as either Class F or Class C, reflecting a difference in chemical composition and origin. Class F fly ashes possess largely pozzolanic properties. Class C fly ashes generally possess cementitious as well as pozzolanic properties. ASTM C 618 differentiates Class C and Class F fly ashes based on the sums of the silicon dioxide (SiO_2) + aluminum oxide (Al_2O_3) + iron oxide (Fe_2O_3). For Class C ash, the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ must be greater than or equal to 50%. For Class F fly ash, the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ must be greater than or equal to 70%. The Class C fly ashes essentially contain 15 to 25% calcium, which makes their performance characteristics different from a low-calcium Class F fly ash.

6.2—Fly ash as a cementitious material

Fly ash is a fine residue resulting from the burning of powdered coal at high temperatures. The most common sources of fly ash are electric power-generating stations. Fly ash has become the predominant pozzolan in use throughout the world due to performance and economic factors. Extensive literature is available on the effects of fly ash in both fresh and hardened concrete.

Development of fly ash as a constituent of portland cement concrete was initiated in the U.S. during the early 1930s. Work at the University of California published in 1937 served as the foundation for specifications, methods of testing, and use of fly ash for this application. This work concluded “that where available, fly ashes of suitable fineness and composition can be used with technical benefit and economy to replace 20 to 50% of the amount of portland cement that otherwise would be required to produce concrete of specific strength and durability.” Where durability is a factor, such as in freezing-and-thawing environments, 25% by mass of cementitious material is generally the upper limit. Applications using up to 70% have been successful.

The main constituent of fly ash is silica. Glassy noncrystalline forms of silica, alumina, and iron are principally responsible for the pozzolanic reaction with calcium hydroxide (lime). In concrete, lime results from the hydration of portland cement. Other components of fly ash are calcium, magnesium, sulfur, potassium, and sodium. Class C fly ashes contain less silica, alumina, and iron than the Class F ashes and usually have elevated levels of calcium.

Although the constituents are not necessarily present in the oxide form, it is customary to express chemical analysis results in terms of the oxides of the elements: silica (SiO_2), alumina (Al_2O_3), iron (Fe_2O_3), calcium (CaO), and sulfur (SO_3). Carbon is seldom determined directly, but is often assumed to be approximately equal to the loss on ignition.

6.3—Effect of fly ash on fresh concrete

According to ACI 232.2R, fly ash can have the following effects on fresh or plastic concrete:

- Improve workability;
- Improve pumpability;
- Extend time of set;
- Decrease bleeding;
- Improve consolidation in forms;
- Decrease early rate of strength gain; and
- Reduce heat evolution.

Workability—Workability in fresh concrete is governed by such factors as the age of the fresh concrete, volume of paste, the water-cementitious material ratio, chemical and mineral admixtures and the proportion, grading, amount, shape, and porosity of aggregates. One benefit of the use of fly ash is the increase in paste volume. Fly ash (specific gravity 1.9 to 2.8) occupies about 30% greater volume than an equal mass of portland cement (specific gravity 3.15). When fly ash is substituted for cement on a 1-to-1 basis by mass, the additional volume of fly ash replaces part of the fine aggregate and fills aggregate voids with paste, providing more cohesion and plasticity. A common explanation for the improved workability is that the spherical shape of fly ash particles provides a ball-bearing effect (Fig. 6.1). Not everyone agrees with this simple explanation, however, and there may be other reasons for the improved workability of concrete containing fly ash.

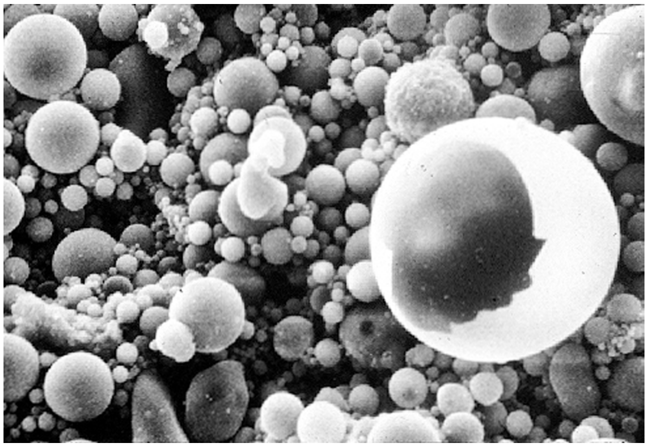
Fig. 6.1—Fly ash particles viewed at 1000x magnification.

Water demand—The use of fly ash as a partial replacement for portland cement will usually reduce water demand for equivalent slump compared to the portland cement only mixture. The degree of water reduction will depend on the mixture proportions, shape and fineness of fly ash particles, as well as characteristics of the aggregates.

Effect on entrained air content—ASTM C 618 sets a limit for the maximum allowable loss on ignition (LOI). The LOI is an indirect measure of the quantity of unburned carbon remaining in the fly ash. Excessive amounts of carbon act as an adsorbent and will affect the dosage of air-entraining admixture required in concrete. Limiting LOI to 6% helps control performance of air-entraining admixtures in concrete. If a fly ash contains an appreciable amount of carbon, it may be difficult to control the air content. Presently two technologies are available to reduce the impact unburned carbon particles have on the ability to reliably entrain air in concrete. One technology uses the principle of turbo-electric charging and electrostatic separation to separate and remove excess carbon particles. The other technology uses a liquid reagent to coat unburned carbon particles. The effects of fly ash and other pozzolans on air content are summarized in Table 6.1.

Pumping—The use of fly ash in pumped mixtures can be beneficial as it reduces segregation and increases cohesiveness. Fly ash helps to fill voids between aggregates, and its spherical particle shape acts as a lubricant in the pump line.

Table 6.1—Effects of supplementary cementitious material on air content

Material	Effects	Guidance
Fly ash	Air content decreases with increased LOI (carbon content).	Changes in LOI or fly ash source require that air-entraining agent dosage be adjusted.
		Perform foam index test to estimate increase in dosage.
	Air void system may be more unstable with some combinations of fly ash/cement/air-entraining agents.	Prepare trial mixtures and evaluate air-void systems.
Ground granulated blast-furnace slag (GGBFS)	Decrease in air content with increased fineness of GGBFS.	Use up to 100% more air-entraining agent for finely ground slags.
Silica fume	Decrease in air content with increase in silica fume content.	Increase air-entraining admixture dosage up to 100% for fume contents up to 10%.
Metakaolin	No apparent effect.	Adjust air-entraining agent dosage if needed.

This lubrication can be used to advantage in one of two ways: if the same flow rate is maintained, the pressure in the pump line will decrease, or if the same line pressure is maintained, flow rates will increase, allowing a greater amount of material to pass through the pipe in a given time (faster placement).

Time of set—Fly ash chemistry may influence setting times. When portland cement is replaced by Class F fly ash, concrete setting times may be slightly extended. The chemical action from Class C fly ash can lead to reduced or extended setting times and may be particularly noticed as ambient and concrete mixture temperatures fall. The longer setting times of concrete mixtures containing fly ash may be shortened by the proper use of an accelerating admixture or may be used to advantage in hot weather concreting.

Bleeding—Excessive bleeding can be controlled by proper proportioning of concrete mixtures. Using fly ash in concrete mixtures usually reduces bleeding. The use of fly ash compensates for a deficiency of fines in the mixture; at the same time, it acts as a water-reducer to promote workability at lower water content. This results in adequate cohesion and plasticity with less water available for bleeding.

Consolidation—Consolidation energy is the amount of effort required to consolidate concrete in formwork and is influenced by both concrete ingredients and proportioning. Concrete mixtures made with fly ash may be easier to compact than those made without. The fineness, void-filling ability, and spherical particle shape all assist in increased response to vibratory energy.

Heat evolution—The hydration of portland cement with water is a reaction that liberates considerable heat. The pozzolanic reaction of Class F fly ash also gives off heat, but to a lesser extent than portland cement. Evolution of heat during hydration is of primary concern in thick or massive concrete sections or for mixtures with high cement contents where the likelihood of differential temperatures from the concrete surface to the center is great enough to result in thermal cracking. Minimizing the heat liberated during the hydration of cementitious materials is the major method of reducing thermal cracking. Class F fly ash and natural pozzolans have been used historically for this purpose. Class C fly ash may behave differently from Class F fly ash in that its heat evolution may be considerably greater, perhaps generating even more heat than the plain concrete mixture. Therefore, use of Class C fly ash in mass concrete should be carefully evaluated.

6.4—Effect of fly ash on hardened concrete

Fly ash can modify the hardened concrete properties in the following ways:

- Increases strength (long-term);
- Has minimal effect on modulus of elasticity;
- Has variable effects on creep and shrinkage;
- Decreases permeability;
- Improves durability; and
- Reduces alkali-aggregate expansion (must be investigated by testing).

Strength—The compressive strength of concrete, for a given set of materials, is primarily dependent upon the water-cementitious materials ratio (*w/cm*). For example, suppose the proportions in Table 6.2 gave mixtures with the same slump for the fresh concrete, and the same compressive strength at 28 days of age. (Note that the concrete with fly ash has a higher water-cement ratio, but a lower water-cementitious materials ratio.)

Curves of *w/cm* versus compressive strength at any given age can be developed for prediction of proportions necessary to yield desired strengths. The three-point curve procedure commonly utilized for plain cement mixtures works well with fly ash mixtures where *w/cm* replaces *w/c*.

Rate of strength gain is dependent upon the cement, fly ash, and water contents. Concrete mixtures proportioned using fly ash as a partial replacement for portland cement can be expected to experience slower strength development at early ages due to the reduced portland cement content. Concrete mixtures proportioned for performance at 28 days of age can use partial cement replacements from 15 to 25% Class F fly ash, depending upon the characteristics of the materials and proportioning. With strength requirement delayed to 56 days, 90 days, or later, dosage rates can be increased to 30 to 50% or more. Many concretes containing Class C fly ash, up to 35%, have similar 28-day strength gain characteristics as plain cement concrete. Where early-age strengths are needed, it's also possible to use other ingredients like chemical accelerators or silica fume to improve the rate of strength gain of the mixture at early ages.

Properly designed concrete mixtures containing fly ash can exhibit higher ultimate compressive strength than portland-cement-only mixtures.

While portland cement continues to hydrate and generate additional strength for many years, the rate of strength gain typically slows down after about 28 days. Fly ash concretes, however, continue to gain strength beyond 28 days at a rate greater than plain portland cement concrete as a result of continued pozzolanic reaction with available calcium hydroxide inside the concrete. Using 28-day strengths for comparison, over time, plain portland cement concrete generally gains about 30% additional strength whereas portland cement/fly ash concrete can gain 50 to 100% additional strength. If 28-day strengths are similar, ultimate strength of fly ash concrete may be greater. Generally, the higher the fly ash content, the greater the potential long-term strength gain. The exact increases will depend upon the characteristics of materials used and proportioning of the mixture.

Flexural strength of fly ash concrete measured at ages as early as 7 days can be expected to be equivalent to a plain portland cement mixture. As a result, the use of fly ash concrete has become widespread in paving applications.

Permeability—Permeability of concrete is affected by cementitious materials content, the water-cementitious materials ratio, aggregate characteristics, water content, curing conditions, air content, and extent of consolidation. Studies have shown that permeability of fly ash concrete is substantially lower than plain portland cement concrete. This effect is due to the pore refinement that occurs as a result of long-term pozzolanic action of fly ash. Reduced permeability of fly ash concrete can decrease the rates (of entry into concrete) of water, corrosive chemicals, oxygen, and carbon dioxide.

Durability—Durability of concrete refers to its ability to resist either physical forces such as repetitive loading, freezing-and-thawing, and abrasion, or chemical attack such as soluble sulfates. Addition of fly ash may improve concrete performance against the various forms of chemical attack.

Replacing portland cement with Class F fly ash lowers the tricalcium aluminate content of the concrete and makes it more resistant to sulfates. Class F ashes generally improve sulfate resistance more efficiently than Class C ashes. Some Class C ashes may even reduce sulfate resistance. Generally, fly ashes containing less than 15% CaO will improve the resistance of concrete to sulfate attack. Other fly ashes may also improve sulfate resistance, but they should be tested using test methods such as ASTM C 1012.

Table 6.2—Strength of mixtures with and without fly ash comparing water-cement and water-cementitious materials ratios

Ingredient	Mixture without fly ash	Mixture with fly ash
Cement, kg (lb)	227 (500)	182 (400)
Fly ash, kg (lb)	—	45 (100)
Water, kg (lb)	123 (270)	113 (250)
Water-cement ratio	0.54	0.63
Water-cementitious materials ratio	0.54	0.50

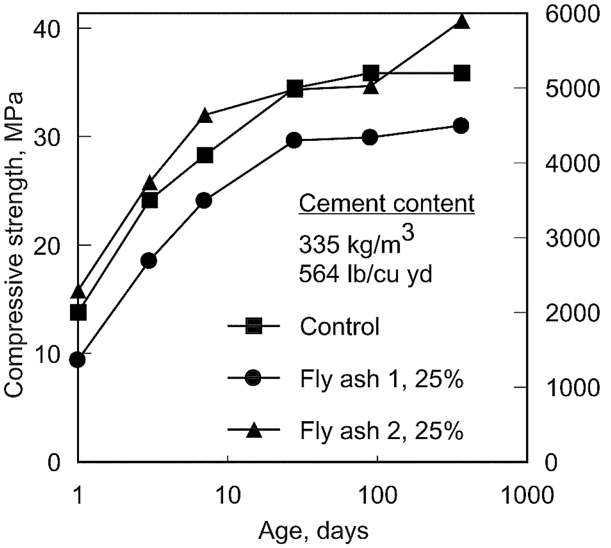

Fig. 6.2—Compressive strength of concrete made with cement and different fly ashes. (Note: compressive strength curves show that fly ash [at 25% replacement] can increase or decrease concrete strength [PCA RD099 data.])

Some acids attack concrete by dissolving the cementitious paste and certain aggregates. Fly ash concrete may slow down the rate of attack from acids (because permeability is reduced). The only known way to protect concrete from aggressive acids, however, is to provide a barrier between the acid and the concrete.

Generally, reinforcing steel is protected against corrosion by the concrete cover and the natural alkalinity of the concrete. Corrosion of reinforcing steel embedded in concrete is accelerated by intrusion of chlorides. Because the permeability of fly ash concrete is reduced, the ingress of chlorides into the concrete will also be reduced and the onset of corrosion may be delayed.

Class F fly ash and some Class N pozzolans have been shown to be effective in reducing expansion from ASR. Class C ashes may or may not improve the performance of concrete susceptible to alkali-silica reaction. When fly ash or natural pozzolans react with calcium hydroxide, alkalies are consumed and held in the cementitious phase where they are kept from the aggregate. Any pozzolanic material should be investigated for its effectiveness in controlling expansion (Fig. 6.3). This can be done by following the methods described in ASTM C 311. Requirements based upon this test are listed in the supplementary optional requirements of ASTM C 618.

Another option is to use a newer, faster test, ASTM C 1260. Although this test is very severe, it can be modified to give quicker results that help establish proper levels of fly ash to add. The modified test is not standardized.

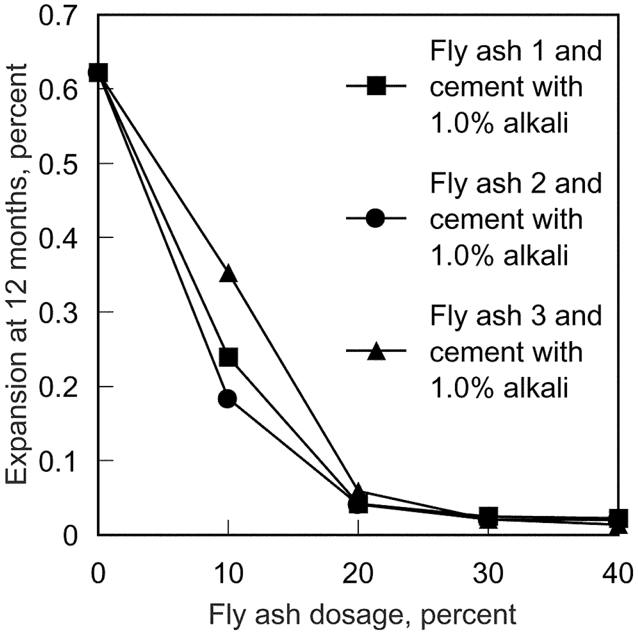

Fig. 6.3—Expansion of concrete mixtures containing alkali silica reactive aggregate and different fly ashes. (Note: fly ash can be used to control alkali-silica reactivity. The required dosage is dependent on the fly ash.)

Resistance to freezing and thawing—The resistance to damage from freezing and thawing of concrete made with or without fly ash depends upon the adequacy of the air-void system, the soundness of the aggregates, age, maturity of the cement paste, and moisture condition of the concrete (Larson et al. 1964). Because of the often slower strength gain of concretes with Class F fly ash, more cementitious material (cement plus fly ash) may be used in mixtures to achieve comparable strength at 28 days. Care should be exercised in proportioning mixtures to ensure that the concrete has adequate strength when first exposed to cyclic freezing and thawing. ACI 301 places a maximum limit of 25% fly ash and natural pozzolans in concrete that will be exposed to de-icing chemicals.

Abrasion resistance of concrete is related to the compressive strength, quality of aggregate, proportioning of the concrete mixture, and quality of the finishing. Fly ash does not directly influence abrasion resistance, but may lead to increased ultimate strength of concrete, and thus indirectly improve abrasion resistance.

6.5—Concrete mixture considerations with fly ash

Fly ash is a cementitious material. As is true for all materials specified for use in portland cement concrete, different fly ashes may perform differently while meeting the quality requirement of ASTM specifications. It is therefore advisable that actual performance in concrete be determined by testing with trial batches.

Fly ash performance in concrete depends upon the quality and performance of the other constituents of the mixture. If other mixture components change, the fly ash in question should be re-evaluated with trial batches before implementing the change in commercial production.

Fly ash may be used as a partial replacement for or an addition to portland cement. In the mixture design, minimum quantities of portland cement should be maintained to meet requirements for early strengths, setting times, and freezing-and-thawing/deicer salt scaling resistance. Above the minimum cement content desired, fly ash can be utilized for the attainment of workability, strength, and durability.

Whereas portland cement reacts quickly with water, Class F fly ash remains basically inert in plastic concrete. Some Class C fly ashes can react quickly with water and may effect water demand, slump loss, and other fresh concrete properties. Most fly ashes do not interfere with activity of chemical admixtures. The exception would be where air-entraining admixture can be adsorbed by excessive carbon in the fly ash. Fly ash is considered compatible with most chemical admixtures.

For more detailed information on the use of fly ash in portland cement concrete, the reader is referred to ACI 232.2R.

CHAPTER 7—GROUND GRANULATED BLAST-FURNACE SLAG

7.1—Classification of ground granulated blast-furnace slag (GGBFS)

In the production of iron, a blast furnace typically is charged with iron ore, flux stone (limestone or dolomite), and petroleum coke for fuel. The two products obtained from the furnace are molten iron and slag. Consisting primarily of silica and alumina from the iron ore combined with calcium from the flux stone, slag contains the same major elements as portland cement but in different proportions (Table 7.1). GGBFS used as a cementitious material, however, is comprised essentially of glasses. Elements within GGBFS, therefore, tend to exist as part of the glassy constituents. Although some ground slag materials, like GGBFS, exhibit cementitious properties by themselves, the various slag products are referred to as mineral admixtures in this document.

The four methods of processing the molten slag are as follows (Fig. 7.1):

1. *Air-cooled*—The molten slag is allowed to cool in pits, then crushed for use principally as aggregate or railroad ballast. Air-cooled slag is not used as a cementitious material.

2. *Expanded*—The molten slag is treated with controlled quantities of water. This makes a cellular lightweight product. Finely ground expanded slag may have some cementitious value, but its principal use is as a lightweight aggregate in concrete block.

3. *Pelletized*—The molten slag is sprayed with water as it falls on a rapidly rotating drum. This breaks up the slag and flips the pieces into the air, forming pellets. If cooling is sufficiently rapid, some glassy material may be made; and this material, when finely ground, may exhibit significant cementitious properties.

4. *Granulated*—The molten slag is very rapidly cooled by quenching in water, which results in a glassy granular product. It is this glassy material that is the main source of the cementitious properties of the granulated slag. The granulated slag is then ground in mills to a fineness similar to that of portland

Table 7.1—Chemical properties of blast-furnace slag

Constituents reported as oxides, %	Portland cement	Blast-furnace slag*
Lime (CaO)	60 to 66	32 to 45
Silica (SiO_2)	19 to 24	32 to 42
Alumina (Al_2O_3)	3 to 8	7 to 16
Iron (Fe_2O_3)	1 to 5	0.1 to 1.5
Magnesia (MgO)	0 to 5	5 to 15

*Adapted from "Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete (ACI 233R-95)," American Concrete Institute, Farmington Hills, Mich., 1995.

Table 7.2—Types of blended cements that contain slag (ASTM C 595)

Description	Type	Slag content by mass
Slag-modified portland cement	I(SM)	Less than 35%
Portland blast-furnace slag cement	IS	25 to 70%
Slag cement	S	70% or greater

cement. Finely ground granulated blast-furnace slag is a hydraulic cementitious material commonly used in conjunction with portland cement.

Since approximately 85 to 90% of the 26 million tons of blast-furnace slag produced in the U.S. is processed as an air-cooled product, only a small percentage of total slag produced currently is being used as a cementitious material. In today's energy-conscious environment, it is expected that more blast-furnace slag will be processed, either by granulating or pelletizing, for its potential cementitious properties. Energy to produce GGBFS or finely ground pelletized slag is lower than that of cements made from clinker, like portland cement.

In the U.S., ASTM C 989 is the principal specification for GGBFS. ASTM C 989 identifies three grades of GGBFS: 120, 100, and 80. These grades represent the average 28 day strength of a standard mortar mixture containing 50% GGBFS relative to a plain portland cement standard mixture.

ASTM C 595 covers the use of slag in blended cements. Three types of blended cements that contain slag and portland cement in various proportions are described in C 595 and are given in Table 7.2.

The ASTM C 595 blended cements use GGBFS that has been either interground with portland cement clinker or blended intimately with separately ground material. Ground slag can be used as an ingredient in cements covered by ASTM C 1157, a performance specification for hydraulic cements.

7.2—Ground granulated blast-furnace slag as a cementitious material

GGBFS and finely ground pelletized slags are marketed separately to the concrete producer and used as a partial replacement for portland cement. The optimum replacement dosage depends on the cementitious activity of the slag, the chemical and physical characteristics of the portland cement, and also on the properties desired in the concrete. Replacement dosages between 5 and 70% by mass of cementitious material are common. Fineness, glass content, and mineral constituents are generally considered to be important factors regarding the cementitious activity of slag.

Fig. 7.1—Slag in various forms.

7.3—Effects of slag on properties of fresh and hardened concrete

It is difficult to compare the performance of concrete containing only portland cement with concrete containing Type IS cement or with GGBFS added at the time of mixing. Chemical and physical characteristics of the blast-furnace slag and of the portland cement, blast-furnace slag dosage, temperature, curing, and other factors affect the concrete properties. Generally, the comparison with portland cement concrete can be summarized as follows:

- If the slag component is finer than portland cement, greater amounts of an air-entraining admixture may be required to achieve a specific air content;
- Concrete with Type IS cement or with higher dosages of GGBFS added at the mixer usually will have lower heat of hydration;
- Concretes containing slag may show somewhat longer time of setting than straight portland cement mixtures, particularly for moderate and higher dosages and at lower ambient temperatures;
- Concrete with Type IS cement or with GGBFS added to the mixer gains strength more slowly, tending to have lower strength at early ages and equal or higher strength at later ages;
- The degree of curing has a similar effect on both types of concrete;
- Concrete containing GGBFS dosages greater than 35% by mass of cementitious material, have demonstrated an improvement in the resistance to sulfate attack, as well as suppression of alkali-aggregate expansion;
- There is no significant difference in the shrinkage characteristics of concrete with and without blast-furnace slag as part of the cementitious materials;
- The freezing-and-thawing resistance of air-entrained concrete with and without slag is similar;
- The color of concrete containing GGBFS or Type IS cement is lighter than normal portland cement concretes; and
- Increasing slag dosage is associated with lower permeability in concrete.

It is believed the amount of granulated and pelletized slag used in concrete will continue to increase, principally through blended cements and GGBFS products.

CHAPTER 8—SILICA FUME

8.1—Silica fume production

Silica fume is a by-product of the silicon and ferrosilicon metal manufacturing process. This finely divided, glassy powder results from the condensation of silicon oxide gas. Silica fume is composed primarily of silicon dioxide (SiO_2). Particles are about 100 times smaller than the typical particles of portland cement. Silica fume is a very reactive pozzolanic material.

Silica fume is transported, stored, and used in three typical forms: as produced powder, slurry, and dry densified powder. The as-produced powder is low in bulk density (128 to 433 kg/m^3 [8 to 27 lb/ft^3]) is difficult to transport and handle, and can create a severe dust problem. The slurried form consists of silica fume and water, usually in equal amounts by mass. Some slurry products may contain chemical admixtures such as water reducers or high-range water reducers. Slurries should be kept agitated prior to batching in concrete. Due to the large volume of slurry commonly used, 50 L/m^3 (10 gal./yd^3) or more, special dispensing equipment is required. Since water is a main ingredient of the slurry, it is necessary to subtract an equal amount of water from the mixing water in order to maintain the same water-cementitious materials ratio (*w/cm*). The dry densified form of silica fume has been processed to increase the bulk density to about 560 to 640 kg/m^3 (35 to 40 lb/ft^3). This form is transported and handled similarly to portland cement or fly ash. Testing has shown no significant differences in the performance of the various forms of silica fume.

8.2—Silica fume as a cementitious material

Silica fume is typically used in quantities ranging from 7 to 12% of the mass of the cementitious material. Silica fume should conform to requirements in ASTM C 1240.

8.3—Effects of silica fume on properties of fresh and hardened concrete

Silica fume addition benefits concrete in two ways. First, the minute particles physically decrease the void space in the cement matrix—this phenomenon is known as packing. Second, silica fume is an extremely reactive pozzolan.

Silica fume is added to concrete to increase compressive strength or to improve durability. Properly proportioned silica fume concrete can achieve very high early and ultimate compressive strengths. Ready-mixed concrete with compressive strength of nearly 135 MPa (20,000 psi) has been produced in the U.S. using silica fume combined with other admixtures. Silica fume enhances durability primarily by decreasing the permeability of concrete. With its reduced permeability, silica-fume concrete has been extensively used in applications where limiting the entry of chlorides is essential, such as in bridge decks, parking structures, and marine structures.

The fineness of silica fume greatly increases the water demand of a concrete mixture. It is therefore always used with a high-range water-reducing admixture to maintain low water-cementitious materials ratios.

Silica-fume concretes typically used for flatwork applications show little, if any, bleeding. This may lead to plastic shrinkage cracking if precautions are not taken to prevent moisture evaporation from the surface of the concrete. In many countries, silica fume is limited to a maximum of 10% addition rates (by mass /weight of cement) to prevent plastic shrinkage cracking. Finishers must be prepared to prevent plastic shrinkage cracking or crusting by fogging, by using an evaporation retarder, or by using other appropriate means. Once finishers have been properly trained, silica-fume concrete is no more difficult to finish than any other type of concrete. Project specifications should require trial placements using the concrete mixture proportions and the finishing crew that will be used for the actual structure.

CHAPTER 9—ADDITIONAL FACTORS IN THE SELECTION AND USE OF PORTLAND CEMENT

The previous chapters have covered the basic information to assist in the selection of cementitious materials for a particular application, and in the testing and evaluation of these materials. There are, however, a number of miscellaneous topics that should be considered and these are discussed in this chapter.

9.1—Uniformity

Cement is an inherently variable material. Cements supplied from the same mill can have different characteristics from lot to lot. Minor fluctuations in raw material compositions and burning conditions are the main cause of this variability. Some differences persist even after fluctuations have been smoothed out by blending in the storage silos.

9.1.1 *Strength variations*—The most important property affected by variability is strength. ASTM C 150 only sets a minimum strength requirement, which is exceeded by most manufacturers. However, the concrete producer is often concerned with minimizing strength variations in concrete, and this is somewhat influenced by the variability of the cement manufacturing process. Testing data acquired in accordance with ASTM C 917 enables the cement consumer to make such an estimate of statistical history of strength variations for use in controlling strength of concrete mixtures.

9.1.2 *Color variations*—There can be considerable color variations between different brands of the same type of cement. This depends on the amount of Fe_2O_3 and MgO (both affecting the amount and color of the ferrite phase, which is responsible for cements' gray color). When patching and repair work are being carried out on new structures, cement from a single source should be used to minimize color variations. On old concrete structures, an acceptable match of color should be sought. However, it should be remembered that color variations in concrete depend not only on the cement, but on many other factors such as the amount of admixtures (especially calcium chloride), type and amount of curing, contamination on the form face, texture or finish technique, water-cement ratio, and color of the sand.

9.2—Handling and storage of cement

Today, cement is most often transported in bulk, and transferred pneumatically from carrier to storage silo. Cement should normally flow well if it is kept free of moisture, and flow is generally improved by the use of processing additions during manufacturing. Bag cement should be stored so that it is protected from direct contact with moisture or other contamination from the environment, and preferably in well-ventilated surroundings. If hard lumps are found (warehouse set) in either bulk or bag cement, it is likely that the cement has been in contact with moisture and its quality may be impaired. Standard tests to determine its strength gain characteristics and setting times should be carried out.

9.2.1 *Cement temperature*—Cement can be at very high temperatures when it is placed in the storage silos at the plant and this heat is dissipated slowly. Therefore, in the summer months when demand is high, cement may still be warm when it is delivered to the concrete plant or job site. The cement should be satisfactory even if the temperature is as high as 77 C (170 F). A problem of early stiffening and increased water demand may develop in very hot weather if the concrete temperatures become too high, but this can be controlled by lowering the temperature of the other ingredients. For each 5.6 C (10 F) increase in cement temperature, the temperature of the concrete will increase about 0.6 C (1 F). Therefore, only in those cases where the concrete temperature is near an upper control or specification limit might an increase in cement temperature cause problems.

9.3—Availability

Although ASTM C 150 recognizes five types of portland cement, not every type is available in all parts of the U.S. Type I and Type II are readily available in most areas, but other types may not be available within a reasonable shipping distance. Type III is generally used for special applications requiring high early strengths. Type IV is rarely made in the U.S., and Type V may be made only on request in some areas. Availability of blended cements and other specialty cements is even more limited. The user should investigate other options available, such as the use of admixtures, different cement contents, etc., to determine the most economical and reliable means of achieving the desired result.

CHAPTER 10—REFERENCES

AASHTO M85, Specification for Portland Cement, American Association of State Highway and Transportation Officials, Washington, D.C.

ACI Committee 225, "Guide to the Selection and Use of Hydraulic Cements (ACI 225-99)," American Concrete Institute, Farmington Hills, Mich.

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CHAPTER 11—RELATED ASTM STANDARDS

1999 Annual Book of ASTM Standards, V. 04.01—Cement; Lime, Gypsum, ASTM, West Conshohocken, Pa.

C 91	Standard Specification for Masonry Cement
C 109	Test for Compressive Strength of Hydraulic Cement Mortars
C 114	Chemical Analysis of Hydraulic Cement
C 115	Test of Fineness of Portland Cement by the Turbidimeter
C 150	Specification for Portland Cement
C 151	Test for Autoclave Expansion of Portland Cement
C 183	Sampling Hydraulic Cement
C 185	Test for Air Content of Hydraulic Cement Mortar
C 186	Test for Heat of Hydration of Hydraulic Cement
C 187	Normal Consistency of Hydraulic Cement
C 191	Test for Time of Setting of Hydraulic Cement by Vicat Needle
C 204	Test for Fineness of Portland Cement by Air Permeability Apparatus
C 219	Definition of Terms Relating to Portland Cement
C 260	Standard Specification for Air Entraining Admixtures for Concrete
C 266	Test for Time of Setting of Hydraulic Cement by Gilmore Needles
C 311	Standard Test Method for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete
C 359	Test for Early Stiffening of Portland Cement (Mortar Method)
C 441	Standard Test Method for Effectiveness of Mineral Admixtures or Ground Blast Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Aggregate Reaction
C 451	Test for Early Stiffening of Portland Cement (Paste Method)
C 452	Test for Potential Expansion of Portland Cement Mortars Exposed to Sulfate
C 595	Specification for Blended Hydraulic Cements

C 618	Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for use as a Mineral Admixture in Concrete
C 807	Test for Time of Setting of Hydraulic Cement Mortar by Vicat Needle
C 845	Specification for Expansive Hydraulic Cement
C 917	Evaluation of Cement Strength Uniformity from a Single Source
C 989	Standard Specification for Ground Granulated Blast Furnace Slag Use in Concrete and Mortars
C 1012	Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
C 1072	Standard Test Method for Measurement of Masonry Flexural Bond Strength
C 1157	Standard Performance Specification for Hydraulic Cement
C 1240	Specification for Silica Fume for Use as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout
C 1260	Standard Test Method for Potential Reactivity of Aggregates (Mortar Bar Method)
C 1328	Standard Specification for Plastic (Stucco) Cement
C 1329	Standard Specification for Mortar Cement

CHAPTER 12—GLOSSARY

Admixture—A material other than water, aggregates, and hydraulic cement that is used as an ingredient in concrete or mortar and is added to the batch immediately before, or during, mixing.

Air entrainment—The inclusion of air in the form of very small bubbles during the mixing of concrete in order to confer frost resistance on the hardened concrete or to improve its workability in a fresh state.

Alkalies—Sodium and potassium (expressed as Na_2O and K_2O) which occur in portland cement, either as solid solutions in the cement compounds, or as water-soluble compounds (for example, sulfates).

Alumina—aluminum oxide (Al_2O_3).

ASR—alkali-silica reaction.

Blast-furnace slag—see Slag (granulated).

Blended cements—A product consisting of a mixture of portland cement and other material such as granulated blast-furnace slag, pozzolan, etc., combined either during the finish grinding of the cement or by blending the material after grinding.

Cement—Clinker interground with gypsum.

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

Cement, portland blast-furnace slag—a hydraulic cement consisting of an intimate interground mixture of portland-cement clinker and granulated blast-furnace slag, or an intimate and uniform blend of portland cement and fine granulated blast-furnace slag in which the amount of the slag constituent is within specified limits.

Cement, portland-pozzolan—a hydraulic cement consisting of an intimate and uniform blend of portland cement or portland blast-furnace slag cement and fine pozzolan produced by intergrinding portland-cement clinker and pozzolan, by blending portland cement or portland blast-furnace slag cement and finely divided pozzolan, or a combination of intergrinding and blending, in which the pozzolan constituent is within specified limits.

Clinker—The partially fused product that is removed from the cement kiln after burning.

Clinkering—The chemical combination of limestone and clay in a cement kiln, which involves melting of part of the kiln charge.

Compound composition—The composition of a portland cement expressed in terms of the percentage by mass of the major chemical compounds it contains.

Diatomaceous earth—a friable earthy material composed of nearly pure hydrous amorphous silica (opal) and consisting essentially of the frustules of the microscopic plants called diatoms.

Dicalcium silicate—belite, C_2S, second main compound in cement.

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

Expansive cement—A modified portland cement that when mixed with water forms a paste which purposely increases in volume during the early hardening period, to a significantly greater degree than pastes containing ordinary portland cement.

False set—Early stiffening that generally occurs within the first few minutes after mixing portland cement with water, without the evolution of much heat. Workability can be restored when the material is remixed.

Final set—An arbitrary measure of the time at which paste, mortar, or concrete is able to resist penetration by a standard weighted test needle.

Fineness—A measure of the degree of subdivision of a finely ground material (powder), such as cement. The parameter used is specific surface area, determined either by turbidimetry (Wagner) or air-permeability (Blaine) measurements.

Flash set—Very rapid stiffening that can occur within minutes when portland cement is mixed with water. Considerable heat is evolved and workability cannot be restored by further mixing without the addition of water.

Fly ash—The finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the firebox through the boiler by flue gases; known in the UK as pulverized-fuel ash (pfa).

Free lime—Calcium oxide (CaO) as in clinker and cement which has not combined with SiO_2, Al_2O_3, or Fe_2O_3 during the burning process, usually because of underburning, insufficient grinding of the raw mixture, or the presence of traces of inhibitors.

Heat of hydration—The heat liberated when hydraulic cements react with water.

Hydration—The chemical reaction between substances and water to form new compounds, called hydration products.

Hydraulic cement—A cement that is capable of setting and hardening in the presence of water due to chemical reactions with water.

Initial set—An arbitrary measure of the time at which paste, mortar, or concrete can resist to a given degree, the penetration of a standard weighted test needle.

Masonry cement—A hydraulic cement specially prepared for use in mortars for masonry construction; the principal cementitious material is generally a hydraulic portland cement with the addition of other finely divided solids.

Mortar—A mixture consisting of sand (fine aggregate), cement, and water.

Natural pozzolan—Either a raw or calcined natural material that has pozzolanic properties (for example, volcanic ash or pumicite, opaline chert and shales, tuffs, and some diatomaceous earths).

Paste or cement paste—A mixture of cement and water without aggregates.

Portland cement—The product obtained by pulverizing clinker, consisting essentially of hydraulic calcium silicates, with calcium sulfates added during grinding; when mixed with water, it forms the binder in portland-cement concrete.

Pozzolan—A siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value, but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Pozzolanic activity index—An index that measures the potential of a pozzolan to react with calcium hydroxide based on the strength of cementitious mixtures containing hydraulic cement with and without the pozzolan; or containing the pozzolan with lime.

Quick set—See Flash set.

Setting—Loss of elasticity and formation of a semi-rigid mass of cement paste, mortar, or concrete.

Silica—Silicon dioxide (SiO_2) occurs in nature as sand, primarily quartz. It is the main constituent of cement (C_3S and C_2S).

Silica fume—Very fine, noncrystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon; also known as condensed silica fume or microsilica.

Slag (granulated)—The glassy, granular material formed when molten blast-furnace slag (a by-product or iron manufacture) is rapidly quenched (cooled); it is blended in a pulverized state with portland cement to form hydraulic mixtures. It consists essentially of silica, or aluminosilica glass containing calcium and other basic elements.

Soundness—The freedom of a solid from cracks, flaws, fissures, or variations from an accepted standard; in the case of a cement, freedom from excessive volume change after setting; in the case of aggregate, the ability to withstand the aggressive action to which concrete containing it might be exposed, particularly that due to weather.

Sulfate resistance—The ability of a material to resist chemical attack by soluble sulfate salts.

Tricalcium silicate—Alite (C_3S) the main compound of cement. It is responsible for early strength.

Tricalcium aluminate—C_3A, the main source of aluminum in cement.

Unsoundness—Cracking of paste, mortar, or concrete caused by excessive, unrestrained volume change (internal expansion) after setting, generally caused by the slow hydration of magnesium oxide or “free lime” calcium oxide.

*Water-cement ratio (*w/c*)*—The mass ratio of the amount of free water (not contained in aggregates) to the amount of cement in a paste, mortar, or concrete.

*Water-cementitious materials ratio (*w/cm*)*—Also called water-binder ratio, the mass ratio of free water (not contained in the aggregates) to the amount of cement plus pozzolan plus slag in a paste, mortar, or concrete.

Workability—That property of freshly mixed paste, mortar, or concrete that determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished.