CHEMICAL ADMIXTURES FOR CONCRETE

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This document discusses commonly used chemical admixtures for concrete and describes the basic use of these admixtures. It is targeted at those in the concrete industry not involved in determining the specific mixture proportions of concrete or in measuring the 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, user's guide, or a technical discussion of past and present research findings. More detailed information is available in ACI Committee Report 212.3R, "Chemical Admixtures for Concrete" and 212.4R, "Guide for the Use of High-Range Water-Reducing Admixtures (Superplasticizers) in Concrete."

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CHAPTER 1—INTRODUCTION

1.1—History

Admixtures have long been recognized as important components of concrete used to improve its performance.

The original use of admixtures in cementitious mixtures is not well documented. It is known that cement mixed with organic matter was applied as a surface coat for water resistance or tinting purposes. It would be a logical step to use such materials, which imparted desired qualities to the surface, as integral parts of the mixture. The use of natural admixtures in concrete was a logical progression. Materials used as admixtures included milk and lard by the Romans; eggs during the middle ages in Europe; polished glutinous rice paste, lacquer, tung oil, blackstrap molasses, and extracts from elm soaked in water and boiled bananas by the Chinese; and in Mesoamerica and Peru, cactus juice and latex from rubber plants. The Mayans also used bark extracts and other substances as set retarders to keep stucco workable for a long period of time.

1.2—Definitions

ACI 116R-00 defines the term admixture as "a material other than water, aggregates, hydraulic cement, and fiber reinforcement, used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing." In ACI 212.3R it is stated that "chemical admixtures are used to enhance the properties of concrete and mortar in the plastic and hardened state. These properties may be modified to increase compressive and flexural strength at all ages, decrease permeability and improve durability, inhibit corrosion, reduce shrinkage, accelerate or retard initial set, increase slump and workability, improve pumpability and finishability, increase cement efficiency, and improve the economy of the mixture. An admixture or combination of admixtures may be the only feasible means of achieving the desired results. In certain instances, the desired objectives may be best achieved by mixture changes in addition to proper admixture usage."

Chemical admixtures are materials that are added to the constituents of a concrete mixture, in most cases, specified as a volume in relation to the mass of the cement or total cementitious materials. The admixtures interact with the hydrating cementitious system by physical and chemical actions, modifying one or more of the properties of concrete in the fresh and/or hardened states.

Concrete is composed principally of aggregates, hydraulic cement, and water, and may contain other cementitious materials and chemical admixtures. It will contain some amount of entrapped air and may also contain purposely entrained air obtained by use of a chemical admixture or air-entraining cement. Chemical admixtures are also frequently used to accelerate, retard, improve workability, reduce mixing water requirements, increase strength, improve durability, or alter other properties of the concrete.

There are many kinds of chemical admixtures that can function in a variety of ways to modify the chemical and physical properties of concrete. This bulletin provides information on the types of chemical admixtures and how they affect the properties of concrete, mortar, and grout.

CHAPTER 2—OVERVIEW

2.1—Function

In ACI 212-3R, the reasons for the use of admixtures are outlined by the following functions that they perform:

- Increase workability without increasing water content or decrease the water content at the same workability;
- Retard or accelerate time of initial setting;
- Reduce or prevent shrinkage or create slight expansion;
- Modify the rate or capacity for bleeding;
- Reduce segregation;
- Improve pumpability;
- Reduce rate of slump loss;
- Retard or reduce heat evolution during early hardening;
- Accelerate the rate of strength development at early ages;
- Increase strength (compressive, tensile, or flexural);
- Increase durability or resistance to severe conditions of exposure, including application of deicing salts and other chemicals;
- Decrease permeability of concrete;
- Control expansion caused by the reaction of alkalies with potentially reactive aggregate constituents;
- Increase bond of concrete to steel reinforcement;
- Increase bond between existing and new concrete;
- Improve impact and abrasion resistance;
- Inhibit corrosion of embedded metal; and
- Produce colored concrete or mortar.

2.2—Standards

Air-Entraining Admixtures	ASTM C 260
Standard Specification for Air-Entraining Admixtures for Concrete	AASHTO M 154
Standard Specification for Air-Entraining Admixtures for Concrete	CRD-C 13
Chemical Admixtures	ASTM C 494
Standard Specification for Chemical Admixtures for Concrete	AASHTO M 194
Standard Specification for Chemical Admixtures for Concrete	CRD-C 87
Calcium Chloride	ASTM D 98
Standard Specification for Calcium Chloride	AASHTO M 144
Foaming Agents	ASTM C 869
Admixtures for Shotcrete	ASTM C 1141
Admixtures for Use in Producing Flowing Concrete	ASTM C 1017
Grout Fluidifier For Preplaced Aggregate Concrete	ASTM C 937
Pigments For Integrally Colored Concrete	ASTM C 979

*ASTM—ASTM International
AASHTO—American Association of State Highway and Transportation Officials
CRD—Army Corps of Engineers, Chief of Research and Development

An admixture may conform to the requirements of one or more of the above types, and may serve more than one of the listed functions. Thus, combinations of two or more admixtures might be used in varying dosages so that optimum results could be obtained using local materials. When using combinations of admixtures, each admixture must be added separately to the concrete mixture. Pre-job testing should be conducted to ensure compatibility of the admixture system. When using admixtures, and particularly combinations of admixtures, testing for compatibility of the admixture system requires knowledge of the rate of slump loss (that is the relationship between slump and time) and the setting time under relatively hot and cold conditions (in addition to laboratory conditions). Test placements on-site are recommended to verify proper workability, finishability, and setting time of the proposed mixture.

CHAPTER 3—AIR-ENTRAINING ADMIXTURES

3.1—History

Air-entraining admixtures are primarily used to stabilize tiny air bubbles in concrete, produced by mixing, and protect against damage from repeated freezing-and-thawing cycles. The dramatic effect of freezing and thawing on concrete is of little surprise to those who live in climates with extensive temperature cycling. Crumbling walls and scaled sidewalks are evidence of the devastating effect that repeated exposure to freezing and thawing can have on concrete proportioned with an inadequate air content and bubble spacing or improperly cured concrete.

During the l930s, certain concrete pavements were more able to withstand the effects of freezing and thawing than others. Investigation showed that the more durable pavements were slightly less dense, and that the cement used had been obtained from mills using beef tallow as a grinding aid in the manufacturing of cement. The beef tallow acted as an air-entraining agent, which improved the durability of the pavements. Later, after rigorous investigation, air-entrained concrete was specified where freezing-and-thawing resistance was needed.

The incorporation of an adequate amount and distribution of entrained air in properly proportioned concrete that contains sound aggregates and is protected from cycles of freezing until the compressive strength reaches about 28 MPa (4000 psi) can render concrete resistant to freezing-and-thawing deterioration. Until recently, the most commonly used air-entraining admixture for concrete was a neutralized wood resin. Now, other formulations that have some enhanced performance properties, such as improved stability, have been introduced. Today, more than 80% of the portland-cement concrete pavements in the United States contain an air-entraining admixture to provide resistance to freezing and thawing and impart better workability, improved homogeneity, and decreased segregation and bleeding.

3.2—Mechanism

Entrained air should not be confused with entrapped air. Air entrainment is usually the result of an addition of a liquid admixture to the concrete during batching, but may be obtained by using a cement blended with a powdered admixture. As a result of the mixing action, these admixtures stabilize air bubbles that become a component of the hardened concrete. The resultant air-void system consists of uniformly dispersed voids throughout the cement paste of the concrete. These tiny voids (between 10 and 1000 micrometers in diameter) must be present in the proper amount and spacing to be effective at providing freezing-and-thawing protection. Concrete made with fine aggregate that is deficient in the smaller particle sizes may benefit from air entrainment.

Table 1—Recommended air contents for concrete exposed to freezing and thawing (ACI 201.2R)

Nominal maximum aggregate size, mm (in.)	Average air content, percent*	
	Severe exposure†	Moderate exposure‡
9.5 (3/8)	7-1/2	6
12.5 (1/2)	7	5-1/2
19 (3/4)	6	5
25 (1)	6	4-1/2
37.5 (1-1/2)	5-1/2	4-1/2

*A reasonable tolerance for air content if field construction is ±1-1/2%.

†Severe exposure—Outdoor exposure in a cold climate where the concrete may be in almost continuous contact with moisture before freezing and where deicing compounds are used. Examples are pavements, bridge decks, and sidewalks.

‡Moderate exposure—Outdoor exposure in a cold climate where the concrete will be only occasionally exposed to moisture before freezing and where no deicing compounds will be used. Examples are certain exterior walls, beams, bridge decks, and slabs not in direct contact with soil.

The space occupied by the mixing water in fresh concrete rarely becomes completely filled with cementitious material reaction product after the concrete has hardened. The remaining spaces are capillary pores. Under saturated conditions, these cavities are filled with water. If this water freezes, the resulting expansion of water to ice creates tremendous internal pressures. The expansion (approximately 9%) when water freezes produces a stress in a confined space. This stress is far in excess of the tensile strength of concrete. The result in non air-entrained concrete is cracking, scaling, and spalling.

Entrained air voids make these capillaries discontinuous. Because the air voids are generally much larger than the passageways, they form tiny reservoirs that act as safety valves during ice expansion, accommodating the increased volume. The importance is not only the amount of entrained air but also the size and spacing of the bubbles. The level of air content recommended by ACI Committee 201 for normal-strength concrete is listed in Table 1. It is based on different exposure conditions and aggregate size. Adding air-entrainment can also improve the finish of the surface of slabs and reduce the occurrence of voids and sand streaking on wall surfaces. Air entrainment, however, is *not* recommended for interior steel troweled floors. Air content in excess of 3% can cause blisters and delamination.

3.3—Use of air-entraining admixtures

Air-entraining admixtures should be required to conform to ASTM Specification C 260.

Air voids should not have a spacing factor larger than 0.2 mm (0.008 in.) for adequate protection of water-saturated concrete in a freezing-and-thawing environment. The term “spacing

Table 2—Factors affecting the air content of concrete at a given dosage of admixture

Factor	Affect on air content
Cement	An increase in the fineness of cement will decrease the air content. As the alkali content of the cement increases, the air content may increase. An increase in the amount of cementitious materials can decrease the air content.
Fine aggregate	An increase in the fine fraction passing the 150 µm (No. 100) sieve will decrease the amount of entrained air. An increase in the middle fractions passing the 1.18 mm (No. 16) sieve, but retained on the 600 µm (No. 30) sieve and 300 µm (No. 50) sieve, will increase the air content. Certain clays may make entraining air difficult.
Coarse aggregate	Dust on the coarse aggregate will decrease the air content. Crushed stone concrete may result in lower air than a gravel concrete.
Water	Small quantities of household or industrial detergents contaminating the water may affect the amount of entrained air. If hard water is used for batching, the air content may be reduced.
Pozzolans and slag	Fly ash, silica fume, natural pozzolans, and ground granulated blast-furnace slag can affect the dosage rate of air-entraining admixtures.
Admixtures	Chemical admixtures generally affect the dosage rate of air-entraining admixtures.
Slump	For less than a 75 mm (3 in.) slump, additional admixture may be needed. An increase in slump to about 150 mm (6 in.) will increase the air content. At slumps above 150 mm (6 in.), air may become less stable and the air content may decrease.
Temperature	An increase in concrete temperature will decrease the air content. Increase in temperature from 21 to 38 °C (70 to 100 °F) may reduce air contents by 25%. Reductions from 21 to 4 °C (70 to 40 °F) may increase air contents by as much as 40%. Dosages of air-entraining admixtures must be adjusted when changes in concrete temperatures take place.
Concrete mixer	The amount of air entrained by any given mixer (stationary, paving, or transit) will decrease as the blades become worn or become coated with hardened concrete buildup. Air contents often increase during the first 70 revolutions of mixing then will hold for a short duration before decreasing. Air content will increase if the mixer is loaded to less than capacity and will decrease if the mixer is overloaded. In very small loads in a drum mixer, however, air becomes more difficult to entrain.

factor" represents the maximum distance that water would have to move before reaching the air-void reservoir or safety valve.

Another factor that must be considered is the size of the air voids. For a given air content, the size of the air voids cannot be too large if the proper spacing factor is to be achieved without using an unacceptable amount of air. The term "specific surface" is used to indicate the average size of the air voids. It represents the surface area of the air voids in concrete per unit volume of air. For adequate resistance to repeated freezing and thawing in a water-saturated environment, the specific surface should be greater than 24 mm^2/mm^3 (600 $in.^2/in.^3$).

With all the benefits a proper air-void system provides, there may also be detrimental effects in concrete. Increasing the air content will typically decrease the strength of concrete. An increase of 1% in air content will typically decrease compressive strength by about 5% in concrete mixtures with a compressive strength in the range of 2l to 35 MPa (3000 to 5000 psi).

The air content of fresh concrete should be closely monitored. Table 2 summarizes some of the factors that influence the entrained air content of fresh concrete.

Additional dosage rates of the various air-entraining admixtures generally range from about 15 to 130 mL per 100 kg (1/4 to 2 fl oz. per 100 lb) of cementitious material. Equipment for dispensing air-entrainment admixtures is discussed in Chapter 9. The measurement of entrained air content should be performed immediately before discharging the concrete into the forms. Samples for acceptance testing, however, should be taken from the middle of the batch in accordance with ASTM C 172. Unit weight should also be checked.

The methods and materials for performing air-content tests on concrete are described in ASTM Standard Test Methods C 231 and C 173. The gravimetric method (ASTM C 138) is not generally used in the field because it requires knowledge of the theoretical unit weight of the concrete on an air-free basis. Unit weights, however, should be monitored in the field to verify uniformity between batch mixture proportions and air contents. Hardened cylinder weight should be recorded on concrete test reports adjacent to compressive strength. Cylinders should be weighed immediately after demolding. Air content should be measured each time concrete is sampled, and air meters should be calibrated regularly. Inexpensive devices for quickly calibrating air meters are available. The Chace Air Indicator, a commonly misapplied device, does not provide the degree of accuracy and precision necessary to measure air content.

For more than 20 years, testing agencies that record hardened cylinder weights have been aware that measured air contents may not be reasonable when compared with hardened cylinder weight. Lower-than-expected strength is often associated with a low hardened cylinder weight, which is not consistent with the measured fresh air content. Subsequent petrographic analysis of a companion cylinder often indicates an air content significantly higher than the measured air content. The air content obtained from the petrographic analysis adequately explains the lower-than-expected cylinder strength, particularly if the air has coalesced around coarse aggregate.

On-site control of air content of fresh concrete requires coordination between the inspector-technician, the concrete supplier, and the concrete contractor. Agreement on procedures and timing of sampling should be made before the start of concrete placement operations. All ingredients must be added to the concrete before testing is initiated. A minimum of 0.04 m^3 (1.0 ft^3) of concrete from the middle of the batch should be discharged into a suitable container, such as a wheelbarrow or concrete buggy, in accordance with ASTM C 172. The remainder of the testing techniques must be performed in strict accordance with ASTM test methods, including proper remixing of the sample.

If the air content is outside specified limits, a retest should be taken immediately. If the air content is found to be too low or too high, the deficiency should be corrected in coordination with the producer, engineer, and testing agency.

Many factors are involved in the assurance of properly air-entrained concrete. Improper concrete placement, consolidation, and finishing techniques may decrease the air content. The configuration of the boom on a pump may affect the air content of the concrete. Tests have shown that there is often more air loss when the boom is in a vertical position as opposed to when the boom is extended in a more horizontal configuration. Attention to proper selection of all materials involved in the proportioning of the mixture is essential, as compatibility problems may exist with other components of the concrete mixture. Materials complying with relevant specifications, including air-entraining admixtures meeting ASTM C 260, and the adherence to proper proportioning procedures is necessary. Proper testing according to standard practices and proper placement and curing of fresh concrete will make a major contribution to obtaining adequate durability and resistance to deterioration by freezing and thawing.

Careful consideration should be given to the need for air-entrainment of steel-troweled slabs. Steel troweling of air-entrained slabs can result in surface scaling. Maximum total air content for interior steel-troweled slabs should normally be 3% to reduce the possibility of scaling. If steel troweling is required, it should be kept to a minimum. Overworking the surface may decrease air entrainment at the surface where it is needed. This also can result in sealing in a layer of water, which will result in scaling.

CHAPTER 4—WATER-REDUCING AND SET-CONTROLLING ADMIXTURES

4.1—Types and composition

Water-reducing, set-controlling admixtures are added to concrete during mixing to increase workability, improve durability, provide easier placement, control the setting time, and produce easier finishing with less segregation of the ingredients. This is accomplished while allowing a reduction of the total water content and providing the ability to control the time of setting to meet changing jobsite and climatic conditions.

The strength improvement resulting from water-reducing admixtures is primarily a result of reducing the water-cementitious materials ratio and increasing cement efficiency. For a given air content, concrete strength is inversely proportional to the water-cementitious materials ratio and, therefore, the reduction in water needed to achieve the desired slump and workability when a water-reducing agent is used will effect an increase in strength. The result of water-reducing admixtures in improving strength, however, often exceeds the results of simply reducing the water content.

Proper use of admixtures should begin by gathering available information and comparing the different types and brands that are available. Trial mixtures, with those admixtures under consideration, should be made to determine their effect on strength, finishability, and other construction requirements, such as rate of slump loss and setting time. Consideration must be given to information such as uniformity, dispensing, long-term performance, and available service. These are points that cannot be assessed by concrete tests but could determine successful admixture use.

The admixture manufacturer should be able to provide information covering typical dosage rates, times of setting, and strength gain for local materials and conditions. The evaluation and application of the admixture should be made with specific job materials using the construction procedures under anticipated ambient conditions. Laboratory tests conducted on concrete with water-reducing admixtures should indicate the effect on pertinent properties necessary for the construction project, including: water requirement, air content, slump, rate of slump loss, bleeding, time of setting, compressive strength, flexural strength, and resistance to freezing and thawing. Following the laboratory tests, field test should be conducted to fully comprehend how the admixtures will work in actual field conditions.

ASTM C 494, "Standard Specification for Chemical Admixtures for Concrete," classifies admixtures into seven types as follows:

Type A	Water-reducing admixtures;
Type B	Retarding admixtures;
Type C	Accelerating admixtures;
Type D	Water-reducing and retarding admixture;
Type E	Water-reducing and accelerating admixtures;
Type F	Water-reducing, high-range, admixtures; and
Type G	Water-reducing, high-range, and retarding admixtures.

Each of the seven types of admixtures covered by ASTM C 494 is designed to function in a specific manner. ASTM C 494 outlines the physical requirements for performance of the potential admixture to be qualified in the respective categories.

To be classified as a Type A (water-reducing) admixture, a minimum water reduction of 5% must be obtained. Initial and final time of setting must be no more than 1 h earlier and not more than an 1.5 h later than the same concrete without the admixture. Compressive strength requirements stated as a percentage of reference are outlined at the various intervals specified for testing. These are stated for both compressive and flexural requirements. Drying shrinkage and freezing-and-thawing resistance are also factors addressed for all types of admixtures in ASTM C 494.

The requirements for compressive strength compared to a control mixture allow no reduction of compressive or flexural strengths for all types except B and C.

In discussing the commercially available water-reducing set-controlling admixtures, it is appropriate to consider five classes of admixtures. Categorized by basic or primary ingredients, they are as follows:

1. Lignosulfonic acids and their salts;
2. Hydroxylated polymers;
3. Hydroxylated carboxylic acids and their salts;
4. Sulfonated melamine or naphthalene formaldehyde condensates; and

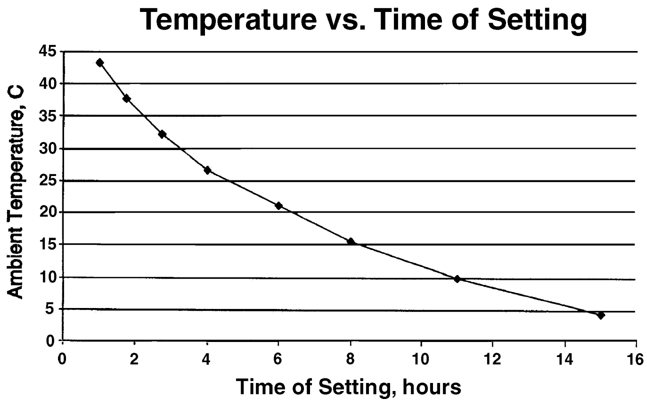

Fig. 1—Relationship between temperature and setting time of concrete.

5. Polyether-polycarboxylates.

Persons involved in concrete construction should possess a basic knowledge of proper use, application, benefits to expect, and cautions to observe for each of these five classes. Members of the first group, salts of lignosulfonic acids or lignins, provide excellent water reduction and produce good strength characteristics. Lignosulfonates tend to entrain air, and can produce sticky, hard-to-finish concrete.

Hydroxylated polymer admixtures are widely used water-reducing admixtures. Some of the benefits associated with these admixtures are:

1. Improved mobility of the concrete. Improved workability and easier placement, reducing the incentive to add water;

2. May reduce segregation, particularly at higher slump ranges;

3. May improve finished appearance and reduce stickiness in finishing flat surfaces, even when used at increased dosages;

4. Does not entrain air and can be used at increased dosages without increasing air contents; and

5. May improve pumpability. This admixture, in a properly proportioned mixture, allows the concrete to be moved with less pressure and provides improved lubrication.

Hydroxylated carboxylic acid-based admixtures, sometimes referred to as HC type admixtures, are designed to reduce water also. Concrete containing HC admixtures is mixed and placed with a higher water content than is the case with other types of water-reducing admixtures. Some HC admixtures promote rapid bleeding from the interior of the concrete. This water must be removed from the surface and the concrete revibrated to ensure proper density in the hardened state. The benefits associated with this admixture type are generally similar to those of the hydroxylated polymer admixtures.

The fourth and fifth groups, sulfonated melamine or naphthalene formaldehyde condensates and polycarboxylates, are discussed in Section 4.5.

4.2—Type A, water-reducing admixtures

The purpose of water-reducing admixtures is stated by ACI Committee 212.3R as: "Water-reducing admixtures are used to reduce the water requirement of the mixture for a given slump, produce concrete of higher strength, obtain specified strength at lower cement content, or increase the slump of a given mixture without an increase in water content." They also may improve the properties of concrete containing aggregates that are harsh, poorly graded, or both, or may be used in concrete that may be placed under difficult conditions. They are useful when placing concrete by means of a pump or tremie."

Typically, the use of Type A water-reducers will decrease mixing water content by 5 to 12%, depending on the admixture, dosage, and other materials and proportions. Dosage rates of water-reducing admixtures depend on the type and amount of active ingredients in the admixture (that is, percent solids content). The dosage is based on the cementitious materials content of the concrete mixture and is expressed as milliliters per hundred kilograms (fluid ounces per hundred pounds) of cementitious materials. Typically the dosage rate of Type A water-reducers range from 130 to 390 mL per 100 kg (2 to 6 fl oz. per 100 lb) of cementitious materials. Higher dosages may result in excessive retardation of the concrete setting time. Manufacturers recommended dosage rates should be followed and trial batches with local materials should be performed to determine the dosage rate for a given concrete mixture. Usually, the primary ingredients of all water-reducing admixtures are organic, which tend to retard the time of setting of the concrete. This retardation may be offset by small additions of chloride or nonchloride accelerating admixtures at the batch plant. Typically, Type A admixtures already contain some accelerators that offset this natural retardation. Care should be taken to ensure that addition of chloride does not exceed the ACI 318 limits for maximum chloride-ion content in reinforced or prestressed concrete.

4.3—Type B, retarding, and Type D, water-reducing and retarding admixtures

4.3.1 *Conventional retarding admixtures*—These two types of admixtures are used for the same basic purpose: to offset unwanted effects of high temperature, such as acceleration of set and reduction of 28-day compressive strength, and to keep concrete workable during the entire placing and consolidation period. Figure 1 indicates the relationship between temperature and setting time of concrete and specifically indicates why retarding admixture formulations are needed in warmer weather.

The benefits derived from retarding formulations include the following:

1. Permits greater flexibility in extending the time of set and the prevention of cold joints;

2. Facilitates finishing in hot weather; and

3. Permits full form deflection before initial set of concrete.

As with Type A admixtures, their dosage rates are based on the amount of cementitious materials in the concrete mixture. While both Type B and Type D provide some water-reduction, Type D is more effective in achieving this goal. The amount of retardation depends upon many factors including: admixture concentration, dosage rate, concrete proportions, and ambient and concrete temperatures.

Different sources and types of cement or different lots of cements from the same source may require different amounts of the admixture to obtain the desired results because of variations in chemical composition, fineness, or both. The effectiveness of the admixture seems to be related primarily to the amount of tricalcium aluminate (C_3A) and the alkali (Na_2O and K_2O) content of the cement.

The time at which the retarding admixture is introduced into the concrete may affect the results. Allowing the cement to become totally wet and delaying admixture addition until all other materials are batched and mixed may result in increased retardation and greater slump increase.

Increased retardation may also be obtained with a higher dosage of the retarding admixture. When high dosages of retarding admixture are used, however, rapid stiffening can occur with some cements, resulting in severe slump loss and difficulties in concrete placement, consolidation, and finishing.

4.3.2 *Extended-set admixtures*—Recent advances in admixture technology have resulted in the development of highly potent retarders called extended-set admixtures, which are capable of stopping the hydration of portland cement, thereby providing a means to control the hydration and setting characteristics of concrete. The effectiveness of extended-set admixtures has been attributed to their ability to retard the reaction of all the major cement constituents, unlike conventional retarding admixtures that only act upon some of the cement constituents.

Extended-set admixtures are used in three primary applications: stabilization of concrete wash water, stabilization of returned plastic concrete, and stabilization of freshly batched concrete for long hauls. The use of extended-set admixtures in stabilization of concrete wash water eliminates the dumping of water that is used to wash out a ready-mixed concrete truck drum while keeping the fins and inner drum clean. The process is relatively simple and involves the addition of low dosages of the extended-set admixture to the wash water to control the hydration of concrete stuck to the fins and inside the drum. The stabilized wash water may be included in the mixing water for fresh concrete that is batched the next day or after a weekend. The setting and strength development characteristics of concrete are not adversely affected by the use of stabilized wash water.

The use of extended-set admixtures to stabilize returned unhardened concrete has made it possible to reuse such concrete during the same production day or the next day in lieu of disposal. The dosage of extended-set admixture required depends on several factors that include the ambient and concrete temperatures, the ingredients used in the manufacture of the concrete, and the age of the concrete. Stabilized concrete is reused by batching fresh concrete on top of the stabilized concrete. In overnight applications, an accelerating admixture may be used to reinitiate the hydration process before adding fresh concrete. Increasingly, extended-set admixtures are being used for long hauls and to maintain slump and concrete temperature during transit, especially in warm weather. For this application, the extended-set admixture is added during or immediately after batching, and the required dosage is established based on the amount of retardation desired.

4.4—Type C, accelerating, and Type E, water-reducing and accelerating admixtures

Accelerating admixtures are added to concrete to shorten the setting time and accelerate the early strength development of concrete. Figure 1, which shows the relationship between temperature and setting time of concrete, specifically indicates why accelerating admixture formulations are needed.

Some widely used and effective chemicals that accelerate the rate of hardening of concrete mixtures, including calcium chloride, other chlorides, triethanolamine, silicates, fluorides, alkali hydroxide, nitrites, nitrates, formates, bromides, and thiocyanates.

The earlier setting time and increased early strength gain of concrete brought about by an accelerating admixture will result in a number of benefits, including reduced bleeding, earlier finishing, improved protection against early exposure to freezing and thawing, earlier use of structure, and reduction of protection time to achieve a given quality. Accelerators do not act as anti-freeze agents; therefore, protection of the concrete at early ages is required when freezing temperatures are expected.

Although calcium chloride is the most effective and economical accelerator for concrete, its potential to cause corrosion of reinforcing steel limits its use. ACI Committee 318 suggests that the water-soluble chloride-ion content should be limited to the following levels for the conditions described:

1. Prestressed concrete—0.06% by mass of cementitious material; and
2. Reinforced concrete—0.15% by mass of cementitious material.

Note that the amount of calcium chloride that may be used is based on the cement content of the concrete mixture.

The following guidelines should be considered before using calcium chloride or chloride-bearing admixture:

1. It should not be used in prestressed concrete because of its potential for causing corrosion;
2. The presence of chloride ion has been associated with corrosion of galvanized steel such as when this material is used as permanent forms for roof decks;
3. Where sulfate-resisting concrete is required, calcium chloride should not be used;
4. Calcium chloride should be avoided in reinforced concrete in a moist condition. In non-reinforced concrete, the level of calcium chloride used should not exceed 2% by weight of cementitious material;
5. Calcium chloride should be dissolved in a portion of mixing water before batching because undissolved lumps may later disfigure concrete surfaces;
6. Calcium chloride precipitates most air-entraining agents so it must be dispensed separately into the mixture; and
7. Field experience and laboratory tests have demonstrated that the use of uncoated aluminum conduit in reinforced concrete containing 1% or more of calcium chloride may lead to sufficient corrosion of the aluminum to collapse the conduit or crack the concrete.

Non-chloride accelerating admixtures containing salts of formates, nitrates, nitrites, and thiocyanates are available from admixture manufacturers. These nonchloride accelerators are effective for set acceleration and strength development: however, the degree of effectiveness of some of these admixtures is dependent on the ambient temperature and concrete temperature at the time of placement.

Some formulations will give protection against freezing to concrete placed in sub-freezing ambient temperatures. These non-chloride accelerating admixtures offer year-round versatility because they are available to be used for acceleration purposes in cool weather and for sub-freezing protection.

The role water-reducing set-controlling admixtures play in achieving control of concrete quality continues to grow as the admixtures are improved. They are used in all types of concrete construction to achieve a wide range of benefits.

4.5—High-range water-reducing admixtures

The primary difference between these admixtures and conventional water-reducing admixtures is that high-range water-reducing (HRWR) admixtures, often referred to as superplasticizers, may reduce the water requirement by more than 30%, without the side effect of excessive retardation. By varying the dosage rate and the amount of mixing water, an HRWR admixture can be used to produce:

1. Concrete of normal workability at a lower water-cementitious material (*w/cm*) ratio;
2. Highly flowable, nearly self-leveling concrete at the same or lower *w/cm* as concrete of normal workability; and
3. A combination of the two; that is, concrete of moderately increased workability with a reduction in the *w/cm*.

When used for the purpose of producing flowing concrete, HRWR admixtures facilitate concrete placement and consolidation.

HRWR admixtures should meet the requirements of ASTM C 494 for classification as Type F, High-Range Water-Reducing, or Type G, High-Range Water-Reducing and Retarding, admixtures. When used to produce flowing concrete, they should also meet the requirements of ASTM C 1017 Type 1, Plasticizing, or Type 2, Plasticizing and Retarding Admixtures. HRWR admixtures are organic products that typically fall into three families based on ingredients:

1. Sulfonated melamine-formaldehyde condensate;
2. Sulfonated naphthalene-formaldehyde condensate; and
3. Polyether-polycarboxylates.

HRWR admixtures act in a manner similar to conventional water-reducing admixtures, except that they are more efficient at dispersing fine-grained materials such as cement, fly ash, ground granulated blast-furnace slag, and silica fume. The most widely used HRWR admixtures do not entrain air but may alter the air-void system. Concrete containing HRWR admixtures, however, may have adequate resistance to freezing and thawing even though the spacing factors may be greater than 0.2 mm (0.008 in.). HRWR admixtures based on polyether-polycarboxylate technology are different chemically and more effective than those based on sulfonated melamine-formaldehyde and sulfonated naphthalene-formaldehyde condensates and, as a result, are typically added at the batch plant. Polyether-polycarboxylate HRWRs also retard less and develop strength faster compared to the other HRWR formulations. Because of their increased efficiency, polyether-polycarboxylate HRWRs are gaining widespread acceptance, particularly in precast concrete applications and in making self-consolidating concrete, a high-performance concrete with high flowability that requires minimal or no vibration for consolidation.

A characteristic of some HRWR admixtures is that their slump-increasing effect is retained in concrete for only 30 to 60 min, by which time the concrete will revert to its original slump. The amount of time that the concrete retains the increased slump is dependent upon the type and quantity of cement, the temperature of the concrete, the type of HRWR admixture, the dosage rate used, the initial slump of the concrete, the mixing time, and the thoroughness of mixing. Because of the limited workability time, HRWR admixtures are typically added at the jobsite. With some HRWR admixtures, it is possible to redose the concrete to regain the increased workability. Generally, the strength is increased and the air content is decreased. HRWR admixtures that offer extended slump life are also commercially available. These HRWR admixtures are typically added at the batch plant.

HRWR admixtures can be used with conventional water-reducers or retarders to reduce slump loss and stickiness, especially in silica-fume concrete mixtures. Because a lower dosage of HRWR admixture may be required in such instances, there may be some savings. These combinations of admixtures may also cause unanticipated or excessive set retardation.

The strength of hardened concrete containing HRWR admixtures is normally higher than that predicted by the lower *w/cm* alone. As with conventional admixtures, this is believed to be due to the dispersing effect of HRWR admixtures on the cement and other cementitious or pozzolanic materials. Because the *w/cm* of mixtures containing HRWR admixtures are typically low, shrinkage and permeability may also be reduced and the overall durability of the concrete may be increased.

A good summary of benefits and limitations for this class of admixtures can be found in National Ready Mixed Concrete Association (NRMCA) Publication No. 158. Briefly outlined are eight advantages and six limitations as follows:

POTENTIAL ADVANTAGES OF HRWR:

1. Significant water reduction;
2. Reduced cement contents;
3. Increased workability;
4. Reduced effort required for placement;
5. More effective use of cement;
6. More rapid rate of early strength development;
7. Increased long-term strength; and
8. Reduced permeability.

POTENTIAL DISADVANTAGES OF HRWR:

1. Additional admixture cost (the concrete in-place cost may be reduced);
2. Slump loss greater than conventional concrete;
3. Modification of air-entraining admixture dosage;

4. Less responsive with some cement;
5. Mild discoloration of light-colored concrete; and
6. Air-void and color blemishes on exposed and formed finishes.

Therefore, a fundamental knowledge regarding the action of base materials will greatly assist in choosing the appropriate admixture. The choice of specific functional type will vary with jobsite conditions.

4.6—Mid-range water-reducing admixtures

Water-reducing admixtures that provide moderate water reduction without significantly delaying the setting characteristics of concrete are also available. Because these admixtures provide more water reduction than conventional water-reducers but less water-reduction than high range water-reducers, they are referred to as mid-range water-reducing admixtures. These admixtures can help reduce stickiness and improve finishability and pumpability of concrete including concrete containing silica fume, or manufactured or coarse sand. Mid-range water-reducing admixtures are typically used in a slump range of 125 to 200 mm (5 to 8 in.) and may entrain additional air. Therefore, evaluations should be performed to establish air-entraining admixture dosage for a desired air content.

CHAPTER 5—CORROSION-INHIBITING ADMIXTURES

Reinforcing steel corrosion is a major concern with regard to the durability of reinforced concrete structures. Each year, numerous bridges and parking garage structures undergo extensive rehabilitation to restore their structural integrity as a result of corrosion damage. In addition to bridges and parking structures, other reinforced concrete structures exposed to chlorides in service are also at risk of corrosion attack. Chlorides are one of the causes of corrosion of steel in concrete. They can be introduced into concrete from deicing salts that are used in the winter months to melt snow or ice, from seawater, or from the concrete mixture ingredients.

There are several ways of combating chloride-induced corrosion, one of which is the use of corrosion-inhibiting admixtures. These admixtures are added to concrete during batching and they protect embedded reinforcement by delaying the onset of corrosion and also reducing the rate of corrosion after initiation. There are several commercially available inhibitors on the market. These include an inorganic formulation that contains calcium nitrite as the active ingredient and organic formulations consisting of amines and esters. As with all admixtures, the manufacturer's recommendations should be followed with regard to dosage.

CHAPTER 6—SHRINKAGE-REDUCING ADMIXTURES

The loss of moisture from the concrete as it dries results in a volume contraction termed drying shrinkage. Drying shrinkage tends to be undesirable when it leads to cracking due to either internal or external restraint, curling of floor slabs, and excessive loss of prestress in prestressed concrete applications. The magnitude of drying shrinkage can be reduced by minimizing the unit water content of a concrete mixture, and using good-quality aggregates and the largest coarse-aggregate size and content consistent with the particular application. Drying shrinkage can also be reduced significantly by using shrinkage-reducing admixtures. These are organic-based formulations that reduce the surface tension of water in the capillary pores of concrete, thereby reducing the tension forces within the concrete matrix that lead to drying shrinkage. Manufacturer's recommendations should be followed with regard to dosage and suitability for use in freezing-and-thawing environments.

CHAPTER 7—ADMIXTURES FOR CONTROLLING ALKALI-SILICA REACTIVITY

Alkali-silica reactivity (ASR) is a reaction between soluble alkalies in concrete and reactive silica in certain types of aggregate that results in the formation of a water-absorptive gel that expands and fractures the concrete. The reaction is typically slow and is dependent on the total amount of alkali present in the concrete, the reactivity of the aggregates and the availability of moisture. ASR can be mitigated by using low-alkali cement, sufficient amounts of pozzolans or ground granulated blast-furnace slag, and if economically feasible, non-reactive aggregates. Alternately, ASR can be mitigated by using lithium-based chemical admixtures. Lithium compounds are effective in reducing ASR because they form a nonabsorptive gel with the reactive silica in the aggregates. The high cost of lithium-based admixtures, however, has greatly limited their use to date.

CHAPTER 8—ADMIXTURES FOR UNDERWATER CONCRETING

Placing concrete underwater can be particularly challenging because of the potential for washout of the cement and fines from the mixture reducing the strength and integrity of the in-place concrete. Although placement techniques, such as tremies, have been used successfully to place concrete underwater, there are situations where enhanced cohesiveness of the concrete mixture is required, necessitating the use of an antiwashout or viscosity-modifying admixture (VMA). Some of these admixtures are formulated from either cellulose ether or whelan gum, and they work simply by binding excess water in the concrete mixture, thereby increasing the cohesiveness and viscosity of the concrete. The overall benefit is a reduction in washout of cement and fines, resistance to dilution with water as the mixture is placed, and preservation of the integrity of the in-place concrete. Proper placement techniques should be followed even with concrete treated with an antiwashout admixture.

CHAPTER 9—EFFECTIVENESS OF ADMIXTURES

The effectiveness of any admixture will vary depending on its concentration in the concrete and the effect of the various constituents of the concrete mixture, particularly the cement. Each class of admixture is defined by its primary function. It may have one or more secondary functions, however, and its use may affect, positively or negatively, concrete properties other than those desired. Therefore, adequate testing should be performed to determine the effects of an admixture on the plastic and hardened properties of concrete such as slump, air content, time of setting, rate of slump loss or relationship of slump and time, and strength development. In addition, testing should be performed to determine the effect of the admixture on other concrete properties that may be of interest, for example, drying shrinkage, modulus of elasticity, or permeability. The final decision as to the use of any admixture and the brand, class, or type, depends on its ability to meet or enhance specific concrete performance needs.

Many of the improvements can be achieved by proper selection and application of specific admixtures. The selection process should focus on the functional qualities required by structural demands, architectural requirements, and contractor needs.

Whatever the approach, be it a single water-reducing admixture or a combination approach, the use of admixtures can be beneficial. Admixtures provide additional means of controlling the quality of concrete by modifying some of its properties, however, they cannot correct for poor-quality materials, improper proportioning of the concrete, and inappropriate placement procedures.

CHAPTER 10—ADMIXTURE DISPENSERS

10.1—Industry requirements and dispensing methods

The subject of liquid admixture dispensers covers the entire process from storage at the producer's plant to introduction into the concrete batch before discharge. Their operation may be separated into four functions:

1. The dispenser transports the admixture from storage to the batch;
2. The dispenser measures the quantity of admixture required;
3. The dispenser provides verification of the volume dispensed; and
4. The dispenser injects the admixture into or onto the batch.

These are the basic functions. In practice, some of the functions may be combined, for example, measurement and verification. For reliability, the functions may be interlocked to prevent false or inaccurate batching of the admixture and to dispense the admixture in the optimal sequence in the concrete production process.

The various systems of dispensing, their applications to specific types of concrete production, and the practical limitations of their operation and accuracy are the subjects that will be discussed in this section. They are important because the successful use of any chemical admixture stands on accurate measurement and correct addition of the material to the concrete batch.

10.2—Liquid admixture dispensing methods

The three most commonly used dispenser systems at ready-mix plants are Systems 1, 2, and 3.

System 1—System 1 is a fully automatic dispenser system for interfacing with the batch plant's automation. It is designed for the ready-mix plant operation, which already has admixture dispensing control capabilities built into its computerized batch control panel. These systems are capable of controlling multiple admixtures at the same time with various interlocks for system compliance to regulatory requirements.

The basic components of this dispenser system includes:

- A metering device for volumetric measurement;
- A measuring unit for visual verification of admixture being dispensing;
- Air-/electric-operated valves for automatic control of the flow of admixture in and out of the measuring unit; and
- A storage tank with fill adapters for connection to the admixture pump.

An interface sub-junction box and cabling for connection to the computerized batch control panel and dispenser system is used. This system may come preassembled in its own protective enclosure or may be assembled at the plant in a protected area.

System 2—System 2 is designed for the ready-mix plant operation that does not have admixture dispenser control capabilities built into its batch panel automation and, therefore, will require a stand-alone admixture batch-control unit to automatically and simultaneously control the dispensing of multiple admixtures. These units often have the capability of being remote started by a signal provided through the plant's automation system.

The basic components of this dispenser system include:

- A metering device for volumetric measurement;
- A measuring unit for visual verification of admixture being dispensing;
- Air-operated valves for automatic control of the flow of admixture in and out of the measuring unit;
- A storage tank with fill adapters for connection to the admixture pump; and
- A stand-alone control unit.

This system may come preassembled in its own protective enclosure or may be assembled at the plant in a protected area.

System 3—System 3 is a manual dispenser system for ready-mix plants that are not automated. The operator controls the quantity of admixture requirements by means of a manual three-position pneumatic valve and visually verifies the correct amount of admixture before dispensing.

The basic components of this dispenser system includes:

- A measuring unit for manual verification of the amount of admixture being dispensed;
- Air-operated valves for manual control of the flow of admixture in and out of the measuring unit;
- A storage tank with fill adapters for connection to a pump; and
- A three-position pneumatic valve and miscellaneous fittings that will be located in the batch control room of the plant.

This system in most cases is assembled at the plant in a protected area.

10.3—Accuracy requirements

Standards of operation for admixture dispensers are specified by scientific groups, concrete producers' trade organizations, and government agencies with authority over concrete production contracts.

The NRMCA and ASTM C 94 specify a batching tolerance of 3% of the required volume or the minimum recommended dosage rate per unit of cement, whichever is greater. (1.3.5.3) ACI 212.1R recommends an accuracy of 3% of the required volume, or 15 mL (1/2 fl oz.), whichever is greater.

10.4—Application considerations and compatibility

Admixture dispensing systems are complex, using parts made of different materials. Therefore, the admixture dispensed through this system should be chemically and operationally compatible with these materials.

The basic rules of application and injection are that the admixtures should not be mixed together. This problem is handled in several ways:

1. Injecting admixtures into the waterline at separate points at least 3 ft apart and only when the water is running;
2. Placing the air-entraining admixture on the fine aggregate and injecting the water-reducer into the stationary or truck mixer along with water; and
3. Sequentially discharging the admixtures. The air-entraining admixture is discharged first; and the water-reducer, or combination of water-reducers, is discharged later.

Recommended injection sequences for various admixtures are as follows:

ADMIXTURES	INJECTION SEQUENCE
Air-entraining admixture	With early water or on sand
Water-reducing admixtures	Follow air-entraining solution
Accelerating admixtures	With water, do not mix with air-entraining admixture
High-range water-reducing admixtures	Immediately before discharge for placement or with the last portion of the water at the batch plant
Polycarboxylate high-range water-reducing admixtures	With early water or with the last portion of the water at the batch plant

Generally, it is not necessary to distribute the admixtures throughout the entire water batch to get good dispersion in the mixture.

There is evidence that the timing of injection of water-reducing retarders has important effects on the length of retardation and, to a lesser extent, the slump and air content. A delay of 1 to 5 min between the water addition and dispersing of the retarder may result in a three-fold increase in set retardation time with lignin and polymer retarding admixtures, a one and one-half to two-fold increase in entrained air, and lesser increases in slump.

10.5—Dispensers for high-range water-reducing admixtures

Some high-range water-reducing admixtures have a short-lived effect on the slump of concrete. Therefore, it is expected that these materials will be dispensed as close to placing time as possible. For ready-mix operations, this might mean the use of a truck-mounted dispenser in the form of a calibrated storage tank. The tank will be charged with the admixture at the same time the concrete is loaded. The user can request an increase in slump by injection of a HRWR admixture, and the driver will dispense the required amount into the turning drum. The volume dispensed will be recorded on the delivery ticket. The injection should be performed under pressure through a spray nozzle to thoroughly disperse the admixture into the drum. Field dispensers, consisting of a measuring unit and pump, can be used at the job site.

10.6—Dispenser maintenance

It is incumbent on the concrete producer to take as great an interest in the admixture dispensing equipment as in the rest of the batch plant. Operating personnel should be trained in the proper operation, winterization, maintenance, and calibration of admixture dispensers. Spare parts should be retained as needed for immediate repairs. Regular cleaning and calibration of the systems should be performed by qualified internal personnel or by the admixture suppliers' service representative. Admixtures have too powerful an influence on the quality of the concrete produced for their dispensing to be given cursory attention.

CHAPTER 11—CONCLUSION

Air-entraining and other chemical admixtures have become a very useful and integral component of concrete. Admixtures are not a panacea for every ill the concrete producer, architect, engineer, owner, or contractor faces when dealing with the many variables of concrete, but they do offer significant improvements in both the plastic and hardened state to all concrete. Continued research and development will provide additional reliability, economy, and performance for the next generation of quality concrete.

CHAPTER 12—LIST OF RELEVANT ASTM STANDARDS

C 94 Ready-Mixed Concrete

C 138 Unit Weight, Yield, and Air Content (Gravimetric) of Concrete

C 143 Slump of Hydraulic-Cement Concrete

C 150 Portland Cement

C 173 Air Content of Freshly Mixed Concrete by the Volumetric Method

C 231 Air Content of Freshly Mixed Concrete by the Pressure Method

C 260 Air-Entraining Admixtures

C 494 Chemical Admixtures

C 869 Foaming Agents Used in Making Preformed Foam for Cellular Concrete

C 937 Grout Fluidifier for Preplaced Aggregate Concrete

C 979 Pigments for Integrally Colored Concrete

C 1012 Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution

C 1017 Chemical Admixtures for Use in Producing Flowing Concrete

C 1144 Admixtures for Shotcrete

C 1157 Hydraulic Cements

D 98 Calcium Chloride

CHAPTER 13—GLOSSARY

Admixture—A material other than water, aggregates, hydraulic cement, and fiber reinforcement, used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing.

Admixture, accelerating—An admixture that causes an increase in the rate of hydration of the hydraulic cement, and thus, shortens the time of setting, increases the rate of strength development, or both.

Admixture, air-entraining—An admixture that causes the development of a system of microscopic air bubbles in concrete, mortar, or cement paste during mixing.

Admixture, retarding—An admixture that causes a decrease in the rate of hydration of the hydraulic cement and lengthens the time of setting.

Admixture, water-reducing—An admixture that either increases slump of freshly mixed mortar or concrete without increasing water content or maintains slump with a reduced amount of water, the effect being due to factors other than air entrainment.

Admixture, water-reducing high-range—A water-reducing admixture capable of producing large water reduction or great flowability without causing undue set retardation or entrainment of air in mortar or concrete.

Aggregate, reactive—Aggregate containing substances capable of reacting chemically with the products of solution or hydration of the portland cement in concrete or mortar under ordinary conditions of exposure, resulting in some cases in harmful expansion, cracking, or staining.

Air, entrained—Microscopic air bubbles intentionally incorporated in mortar or concrete during mixing, usually by use of a surface-active agent; typically between 10 and 1000 μm in diameter and spherical or nearly so.

Air, entrapped—Air voids in concrete that are not purposely entrained and are significantly larger and less useful than those of entrained air, 1 mm in diameter or larger in size.

Air content—The total volume of air voids in cement paste, mortar, or concrete, exclusive of pore space in aggregate particles, usually expressed as a percentage of volume of the paste, mortar, or concrete.

Alkali—Salts of alkali metals, principally sodium and potassium, specifically sodium and potassium occurring in constituents of concrete and mortar, usually expressed in chemical analysis as the oxides Na_2O and K_2O.

Alkali-aggregate reaction—Chemical reaction in either mortar or concrete between alkalies (sodium and potassium) from portland cement or other sources and certain constituents of some aggregates, under certain conditions, deleterious expansion of concrete or mortar may result.

Alkali-carbonate reaction—The reaction between the alkalies (sodium and potassium) in portland cement and certain carbonate rocks, particularly calcitic dolomite and dolomitic limestones, present in some aggregates, the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Alkali-silica reaction—The reaction between the alkalies (sodium and potassium) in portland cement and certain siliceous rocks or minerals, such as opaline chert, strained quartz and acidic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Calcium chloride—A crystalline solid, $CaCl_2$; in various technical grades, used as a drying agent, as an accelerator for fresh concrete, a deicing chemical, and for other purposes.

Cement, portland—A hydraulic cement produced by pulverizing portland-cement clinker and usually containing calcium sulfate.

Cementitious—Having cementing properties.

Sulfate attack—Either a chemical or physical reaction or both that occurs between sulfates usually in soil or groundwater and concrete or mortar; the chemical reaction is primarily with calcium aluminate hydrates in the cement-paste matrix, often causing deterioration.

Sulfate resistance—Ability of concrete or mortar to withstand sulfate attack.