

ACI 212.3R-16

Report on Chemical Admixtures for Concrete

Reported by ACI Committee 212



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Report on Chemical Admixtures for Concrete

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Report on Chemical Admixtures for Concrete

Reported by ACI Committee 212

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The committee would like to thank T. Harris, N. Treggar, and C. Talbot for their contributions to this report.

This report reviews several categories and types of chemical admixtures and their use in unique concrete technologies. They are classified into 12 groups: air-entraining; normal, mid- and high-range water-reducing; accelerating; set-retarding; extended set-control; workability-retaining; viscosity- and rheology-modifying; shrinkage-reducing and shrinkage-compensating, and corrosion-inhibiting; lithium admixtures to reduce deleterious alkali-silica reaction; permeability-reducing; and miscellaneous.

Chemical admixtures are used on a daily basis in the cast-in-place and precast concrete industries. Mixture designs using multiple chemical admixtures are more common today. Their successful use requires compatibility, setting times, and early strengths that are appropriate to the placing environment.

Each category of admixture addresses common use and the potential benefits of a properly proportioned concrete mixture to various professionals, including the concrete contractor, concrete producer, and design professional. The sustainability of chemical admixtures and their role in sustainable construction is addressed. Finely divided mineral admixtures, such as fly ash or raw and processed natural pozzolans, are addressed in ACI 232.2R and ACI 232.1R, respectively.

Keywords: accelerating; admixture(s); admixture system; air-entraining; alkali-aggregate reaction; batching order; cold weather concrete; corrosion-inhibiting; extended set control; flowing concrete; high-range water-reducing admixture; mid-range water-reducing admixture; permeability-reducing admixtures; pervious concrete; self-consolidating concrete; set-retarding; rheology-modifying; shrinkage-reducing; water-reducing; viscosity-modifying; workability-retaining.

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ACI 212.3R-16 supersedes ACI 212.3R-10 and was adopted and published March 2016.

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CHAPTER 1—INTRODUCTION**1.1—Introduction**

Chemical admixtures are primarily water-soluble substances used to modify the properties of concrete, mortar, or grout in the plastic state, hardened state, or both. The effects include increased compressive and flexural strength at all ages, decreased permeability and improved durability, corrosion reduction, shrinkage reduction, initial set adjustments, extended set control, increased slump and workability, improved pumpability, finish and finishability, rheology modification, improved cement efficiency, alkali-silica reaction (ASR) reduction, and concrete mixture economy.

An admixture or combination of admixtures may be required to achieve the specific desired results. Proper mixture proportions, however, are required for optimum benefits. In some cases, a desired objective is best achieved by mixture changes in addition to proper admixture usage. Chemical admixtures are not a substitute for suitable concrete mixture proportions and acceptable construction practices.

1.2—Scope

This report deals with state-of-the-art and commonly used admixtures. Materials such as supplementary cementitious materials that are used to produce concrete are only referred to in regards to their interaction with chemical admixtures.

Chapters 1 through 4 address topics that typically apply to all admixtures, Chapters 5 through 16 categorize chemical admixtures generically or with respect to their performance characteristics, and Chapters 17 through 21 provide information on the use of multiple combinations of admixtures in the production of some unique concretes. Information characterizing each category is presented with brief statements of the general purposes and expected effects for each group of materials. The wide scope of admixture technology, the continued entrance of new or modified materials, and the variations of effects with different concreting materials and conditions preclude a complete listing of all admixtures and their effects on concrete. Table 1.2 lists the admixture types addressed in this document and summarizes their effects and benefits in concrete, and typical materials used in their production.

Table 1.2—Admixtures, their characteristics, and usage

Admixture type (Chapter number)	Effects and benefits	Materials
(5) Air-entraining (ASTM C260/C260M; AASHTO M 154M/M 154)	Improve durability in freezing and thawing, deicer, sulfate, and alkali-reactive environments. Improve workability.	Salts of wood resins, some synthetic detergents, salts of sulfonated lignin, salts of petroleum acids, salts of proteinaceous material, fatty and resinous acids and their salts, tall oils and gum rosin salts, alkylbenzene sulfonates, and salts of sulfonated hydrocarbons.
(6) Water-reducing (ASTM C494/C494M; AASHTO M 194M/M 194, Type A)	Reduce water content at least 5 percent.	Lignosulfonic acids and their salts. Hydroxylated carboxylic acids and their salts. Polysaccharides, melamine polycondensation products, naphthalene polycondensation products, and polycarboxylates.
(6) Mid-range water-reducing (ASTM C494/C494M, Type A)	Reduce water content by between 5 and 10 percent without retardation of initial set.	Lignosulfonic acids and their salts. Polycarboxylates.
(6) High-range water-reducing (ASTM C494/C494M; AASHTO M 194M/M 194, Type F or G)	Reduce water content by at least 12 to 40 percent, increase slump, decrease placing time, increase flowability of concrete; used in self-consolidating concrete (SCC).	Melamine sulfonate polycondensation products, naphthalene sulfonate polycondensation products, and polycarboxylates.
(7) Accelerating (ASTM C494/C494M; AASHTO M 194M/M 194, Type C or E)	Accelerate setting and early strength development.	Calcium chloride (ASTM D98; AASHTO M 144), triethanolamine, sodium thiocyanate, sodium/calcium formate, sodium/calcium nitrite, calcium nitrate, aluminates, and silicates.
(8) Set-retarding (ASTM C494/ C494M and AASHTO M 194M/M 194, Type D)	Reduce water content at least 5 percent. Delay set time.	Refer to water-reducing materials.
(9) Extended set-controlling (hydration control) (ASTM C494/C494M, Type B or D)	Used to stop or severely retard the cement hydration process. Often used in wash water and in returned concrete for reuse, and can provide medium- to long-term set retardation for long hauls. Retain slump life in a more consistent manner than normal retarding admixtures.	Carboxylic acids. Phosphorus-containing organic acid salts.
(10) Workability retaining	Provide workability (slump) retention when used in combination with normal-, mid-, or high-range water reducer with no effect on initial slump, set time, or strength gain	Dispersants such as polycarboxylates.
(11) Viscosity- and rheology-modifying	Modify the rheological properties of plastic concrete.	Polyethylene oxides, cellulose ethers (HEC and HPMC), alginates (from seaweed), natural and synthetic gums, and polyacrylamides or polyvinyl alcohol.
(12) Shrinkage-reducing and shrinkage-compensating	Reduce drying shrinkage. Reductions of 30 to 50 percent can be achieved.	Polyoxyalkylene alkyl ether, propylene glycol, calcium sulfoaluminate, calcium-aluminate, calcium hydroxide- or magnesium oxide-based systems
(13) Corrosion-inhibiting (ASTM C1582/C1582M)	Significantly reduce the rate of steel corrosion and extend the time for onset of corrosion.	Amine carboxylates aminoester organic emulsion, calcium nitrite, and organic alkydicarboxylic. Chromates, phosphates, hypophosphites, alkalis, and fluorides.
(14) Lithium admixtures to reduce deleterious expansions from alkali-silica reaction	Minimize deleterious expansions from alkali-silica reaction.	Lithium nitrate, lithium carbonate, lithium hydroxide, and lithium nitrite.
(15a) Permeability-reducing admixture: non-hydrostatic conditions (PRAN)	Water-repellent surface, reduced water absorption.	Long-chain fatty acid derivatives (stearic, oleic, caprylic capric), soaps and oils (tallows, soya-based), petroleum derivatives (mineral oil, paraffin, bitumen emulsions), and fine particle fillers (silicates, bentonite, talc).
(15b) Permeability-reducing admixture: hydrostatic conditions (PRAH)	Reduced permeability, increased resistance to water penetration under pressure.	Crystalline hydrophilic polymers (latex, water-soluble, or liquid polymer).
(16) Miscellaneous admixtures:		
(16a) Bonding	Increase bond strength.	Polyvinyl chloride, polyvinyl acetate, acrylics, and butadiene-styrene copolymers.
(16b) Coloring	Colored concrete.	Carbon black, iron oxide, phthalocyanine, raw burnt umber, chromium oxide, and titanium dioxide.
(16c) Flocculating	Increase interparticle attraction to allow paste to behave as one large flock.	Vinyl acetate-maleic anhydride copolymer.
(16d) Fungicidal, cermicidal, insecticidal	Inhibit or control bacterial, fungal, and insecticidal growth.	Polyhalogenated phenols, emulsion, and copper compounds.
(16e) Air-detraining	Reduce air in concrete mixtures, cement slurries, and other cementing applications.	Tributyl phosphate, dibutyl phosphate, dibutylphthalate, polydimethylsiloxane, dodecyl (lauryl) alcohol, octyl alcohol, polypropylene glycols, water-soluble esters of carbonic and boric acids, and lower sulfonate oils.
(16f) Expansive/gas forming	Control settlement and bleeding and improve the intrusion of grout and mortars.	Metallic aluminum, zinc or magnesium, hydrogen peroxide, nitrogen and ammonium compounds, and certain forms of activated carbon or fluidized coke.
(16g) Cellular	Air-generating admixtures for the production of flowable fill, lightweight concrete, insulation.	Protein and other synthetic surfactants.
(16h) Shotcrete	Shotcrete accelerators for wet and dry mixture applications.	Alkali-based and alkali-free materials.
(16i) MCP	Production efficiency, surface texture and strength.	Plasticizers such as soaps, surfactants, lubricants, and cement dispersants, accelerators both calcium chloride and non-chloride based, and water-repellent/efflorescence control admixtures such as calcium aluminum stearates, fatty acids, silicone emulsions, and wax emulsions.

CHAPTER 2—DEFINITIONS

2.1—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <https://www.concrete.org/store/productdetail.aspx?ItemID=CT13>. Definitions provided herein complement that source.

alkali-silica reaction—generally deleterious dissolution and swelling of siliceous aggregates in the presence of pore solutions comprised of alkali hydroxides; the reaction products may cause abnormal expansion and cracking of concrete.

corrosion inhibitor—chemical compound, either liquid or powder, usually intermixed in concrete that either extends the time to corrosion initiation or significantly reduces the corrosion rate of embedded metal, or both, in concrete containing chlorides in excess of the accepted corrosion threshold value for the metal in untreated concrete

durability—ability of a material to resist weathering action, chemical attack, abrasion, and other conditions of service.

rheology—science dealing with deformation and flow of materials.

slump flow—measure of the unconfined flow potential of a freshly mixed self-consolidating concrete or grout; value is equal to the average of two perpendicular diameters of the material measured to the nearest 1/2 in. (12.5 mm) after it is released from the slump cone and stops flowing.

water repellent—admixture that produces concrete that is resistant, but not impervious, to penetration by water.

yield stress—critical shear stress value below which a viscoplastic material will not flow and, once exceeded, flows like a viscous liquid.

j) Reduce the rate of slump loss

k) Increase placement rate

3.1.2 Modification of hardened concrete, mortar, and grout—Admixtures are used to modify properties of hardened concrete, mortar, and grout. Examples are:

a) Reduce the rate of heat evolution during early cement hydration

b) Accelerate the rate of strength development at early ages

c) Increase strength (compressive, tensile, or flexural)

d) Increase resistance to freezing and thawing

e) Reduce scaling caused by deicing salts

f) Decrease permeability and improve durability

g) Reduce expansion caused by alkali-aggregate reaction

h) Increase bond to steel reinforcement and between existing and new concrete

i) Improve impact resistance and abrasion resistance

j) Inhibit corrosion of embedded metal

k) Produce colored concrete or mortar

l) Reduce drying shrinkage and curling

3.2—Specifications for admixtures

The following standard specifications cover the admixture types that make up the bulk of products covered in this report:

a) Air-entraining admixtures: **ASTM C260/C260M** and **AASHTO M 154M/M 154**

b) Water-reducing and set-controlling admixtures: **ASTM C494/C494M** and **AASHTO M 194M/M 194**

c) Calcium chloride: **ASTM D98** and **AASHTO M 144**

d) Corrosion-inhibiting admixtures: **ASTM C1582/C1582M**

e) Admixtures for use in producing flowing concrete: **ASTM C1017/C1017M**

f) Pigments for integrally colored concrete: **ASTM C979/C979M**

ASTM C494/C494M includes a Type S specialty admixture designation that includes admixtures not covered by other ASTM standards. Results obtained from tests done in accordance with ASTM C494/C494M ensures these products give values that match within limits those of the untreated reference concrete and meet standard requirements.

3.3—Sampling and testing

Admixture samples for testing and evaluation should be obtained by the procedures prescribed for each admixture's specifications using random sampling from plant production, previously unopened packages or containers, or fresh bulk shipments.

Admixtures are tested to determine compliance with specifications; evaluate effects on the properties of concrete made with materials under the anticipated ambient conditions and construction procedures; determine uniformity of the product within or between batches, lots, or containers; or reveal any undesirable effects. The quality-control procedures used by producers of admixtures should ensure product compliance with provisions from ASTM or other applicable specifications, including uniformity. Because a producer's quality-control test methods could be developed to minimize

CHAPTER 3—GENERAL

3.1—Admixture benefits

Chemical admixtures are used singularly or in combination to modify particular properties of concrete or mortar in the plastic state, hardened state, or both. Types and dosages are selected in accordance with climatic conditions for maintaining workability and pumpability, water-cementitious materials ratio (w/cm), air content, setting time, and early and final strengths. Proposed mixtures and admixture choices are often confirmed with successful test placements on site.

3.1.1 Modification of fresh concrete, mortar, and grout—Admixtures are used to modify and improve properties of fresh concrete, mortar, and grout. Examples are:

a) Increase the workability without increasing the water content, or decrease the water content without changing the workability

b) Increase the slump or slump flow without increasing the water content

c) Retard or accelerate the time of initial setting

d) Reduce or prevent settlement

e) Modify bleeding characteristics

f) Reduce segregation

g) Improve finishability

h) Improve pumpability

i) Modify rheological properties

particular proprietary product, they may not be applicable for general use.

ASTM provides procedures for testing concrete containing admixtures. Producing concrete should be preceded by testing that allows observation and measurement of the performance of the admixture under concrete plant operating conditions in combination with the constituent materials that will be used. Uniformity of results is as important as the average result, with respect to each significant property of the admixture or the concrete.

3.4—Cost effectiveness

Economic evaluation of an admixture should be based on the test results obtained when used with the specified concrete under conditions simulating those expected on the jobsite. Characteristics of the cementitious materials and aggregate; their relative proportions; and the temperature, humidity, and curing conditions influence test results. When evaluating an admixture, its effect on the volume of a given batch should be considered. The concrete mixture should yield 27 cubic feet per yard (1 cubic meter), including the volume increase as a result of admixture behavior. All changes in the composition of a unit volume of concrete should be considered when testing the direct effect of the admixture and when estimating its benefits.

The cost effectiveness of an admixture should be based on the cost of the concrete in place, rather than the cost of the concrete alone. The cost in place, which includes transporting, placing, and finishing costs, is of greatest interest to the owner. The admixture benefits can allow the use of less-expensive construction methods or allow structural designs that offset the added cost due to its use. For example, novel and economical structural designs have resulted from the use of high-range water-reducing admixtures (HRWRAs). They are essential ingredients of cost-effective, high-performance concrete.

Water-reducing and set-retarding admixtures permit placement of large volumes of concrete over extended periods, minimizing the need for forming, placing, and joining separate units. Accelerating admixtures reduce finishing and forming costs. Air-entraining and water-reducing admixtures are typically used to meet the required physical properties of lightweight concrete (ACI 213R).

3.5—Selection and evaluation

Pay careful attention to the instructions and recommendations provided by the manufacturer of the admixture. An admixture's effects should be evaluated whenever possible using the specified materials under site conditions.

This is particularly important when:

- a) The admixture has not been used previously with the particular combination of materials
- b) Special types of cementitious materials are specified
- c) More than one admixture is to be used
- d) Mixing and placing is completed at temperatures outside recommended temperature ranges for concrete

The use of admixtures also requires a review of the concrete mixture design constituents. Prime concerns are:

- a) Type and amount of cement

- b) Type and amount of supplementary cementitious materials
- c) Combined aggregate gradation, water, and air content
- d) Climatic conditions

On-site testing of the proposed concrete mixture to verify proper workability, finishability, pumpability, and setting time is recommended.

Several admixtures affect more than one property of concrete. Rapid stiffening and significant retardation are not desirable. The cause of abnormal setting behavior should be determined through studies on compatibility of the admixtures and cementitious material to be used (ASTM C1679; Nkinamubanzi and Aïtein 2004; Roberts and Taylor 2007; Taylor et al. 2006a,b, 2008). Early stiffening is often caused by changes in the reaction rate between the tricalcium aluminate and sulfate ions in solution in the pore fluid. Excessive retardation can be caused by an overdose of admixture or by a lowering of ambient temperature, both of which delay the hydration of the calcium silicates (Hansen 1960).

Another important consideration when using admixtures arises when there is a limit on the measurable amounts of chloride ions permitted in the concrete (ACI 318; ACI 222R). The chloride ion content of these admixtures will be limited by the chloride ions present in the water used for manufacturing. These limits are usually expressed as maximum percent of chloride ion by mass of cement, although the amount of water-soluble chloride ion per mass of cement or concrete is sometimes specified. The procedures of ASTM C1152/C1152M and ASTM C1218/C1218M can be used to measure acid-soluble and water-soluble chloride, respectively, in mortar or concrete. Be sure to know the chloride ion content of an admixture to ensure that its use will not cause the concrete to have a chloride ion content greater than specified. In spite of the misuse of such terms as chloride-free, all admixtures solutions will contain small but measurable amounts of chloride ions coming from municipal drinking water. The trace levels of chloride ions do not influence the risk of corrosion of embedded reinforcement in concrete.

Although specifications deal primarily with the influence of admixtures on specific properties of fresh and hardened concrete, the concrete supplier, contractor, and owner of the construction project may be interested in other features of concrete construction. Of primary concern are workability, pumpability, placing and finishing qualities, early strength development, reuse of forms or molds, or the appearance of formed surfaces. These additional features are important when an admixture is selected and its dosage rate is determined.

Guidance for using different categories of admixtures is given in this report. Those responsible for construction of concrete structures should bear in mind that increasing material costs and continuing development of new and improved admixtures warrant the continuous reevaluation of the benefits of using admixtures.

3.6—Proportioning and batching

The concrete mixture should be proportioned in accordance with ACI 211.1, ACI 211.2, or another method, and provide the specified qualities and characteristics required by the purchaser, project specification, or both. The admix-

tures selected should be compatible with the constituents of the mixture and added separately to the batch. The choice of admixtures will be based on the required water content; w/cm ; compressive and flexural strengths; air content; target slump or slump/flow; setting times; early strength development, if required; and ultimate compressive and flexural strengths. Strength, air content, slump or slump/flow, and setting time can be based on previous experience or trial batches. Workability, finishability, pumpability, setting time, and other characteristics required in the plastic state should be verified with a successful test placement on site.

3.6.1 Liquid batching systems—Although liquid admixtures are not typically batched by mass because mass-batching devices are more expensive than volumetric dispensers, a few concrete plants do use mass-batching systems. In some cases, it is necessary to dilute admixture solutions to obtain a sufficient quantity for accurate measurement by mass. Most methods of batching liquid admixtures require a visual volumetric container called a calibration tube to enable the plant operator to verify accuracy of the admixture dosage. While the simplest batching method consists of a visual volumetric container, others include positive volumetric displacement. Positive displacement flow meters make accurate volumetric flow measurements by taking finite increments or volumes of the fluid. There are several types of admixture batching systems, including: 1) the nutating disk, which is commonly used for liquid admixtures, is one of several similar methods that can be used readily with manual, semiautomatic, and automatic systems, and is operated easily by a remote control with appropriate interlocking in the batch sequence; 2) simple manual dispensing systems, which are designed for low-volume concrete plants and depend on the concrete plant operator batching the proper amount of admixture into a calibration tube and discharging it into the batch; and 3) more sophisticated systems intended for automated high-volume plants provide automatic fill and discharge of a sight or calibration tube.

Adding an admixture at the jobsite can also be accomplished with a tank and pressurized dispensing system. A calibrated holding tank and mechanical or electromechanical dispensing device should be part of the system so the plant operator can verify the proper amount of admixture is batched into the concrete mixer or truck-mounted tank.

Flow meters and calibration tubes equipped with floats or probes are often combined with pulse-emitting transmitters that give readouts on electromechanical or electronic counters. These are often set by inputting the dosage of admixture per unit of cementitious material. The amount of cementitious material input into the batching panel combined with the dosage rate sets the dispensing system to batch the proper amount of admixture. Timer-controlled systems involve the timing of flow through an orifice. Considerable error can be introduced by changes in power supply, partial restrictions of the measuring orifice, and changes in viscosity of the solution and pressure in the line. Viscosity is affected by temperature and admixture concentration. Timer-controlled systems should be recalibrated in accordance with project documents or manufacturer recommendations. The plant

operator should verify the proper admixture dose by observing the calibration tube. Although timer-controlled systems have been used successfully, their use is not recommended except for dispensing calcium chloride solution. Because of the marked effect of admixtures on concrete performance, care and attention to the timing and accuracy of admixture batching are necessary to avoid serious problems. Jobsite introduction of HRWRAs is addressed in **Chapter 6**.

3.6.2 Maintenance—Batching systems require routine periodic maintenance to prevent inaccuracies developing from such causes as sticky valves, buildup of foreign matter in meters, or in storage and mixing tanks or worn pumps.

Components should be protected from dust and temperature extremes, and be kept readily accessible for visual observation and maintenance. Although admixture batching systems are usually installed and maintained by the admixture producer, plant operators should thoroughly understand the system and be capable of performing simple maintenance requirements. Plant operators should verify accuracy of the system on a regular basis, preferably at intervals determined by plant certification programs, state departments of transportation requirements, or admixture producer recommendations, noting any trends that indicate worn parts requiring replacement.

3.6.3 Storage—Admixtures should be stored in strict accordance with the manufacturer's recommendations. Follow instructions regarding the effects of freezing the product (although most admixtures are not damaged by freezing). An admixture stored beyond its recommended shelf life should be retested before use following the manufacturer's recommendation.

3.7—Batching order for adding chemical admixtures in concrete

Concrete can be truck- or plant-mixed and may require incorporation of several chemical admixtures. The resulting concrete should meet specification requirements and the concrete uniformity requirements of **ASTM C94/C94M**. Test samples for verification of specification compliance should be obtained from truckloads of the size that will typically be delivered and sampled at a time after batching is initiated, similar to that expected for jobsite samples. Rate of slump loss and set time should be recorded, as should density and cylinder weight.

Chemical admixtures can be incorporated at more than one location. For example, air-entraining admixtures could be discharged onto sand on the concrete charging conveyor belt, or in the sand hopper. Admixtures can also be added through the plant water feed, or directly into the plant or truck mixer. Admixtures should be added separately to prevent intermixing before incorporation into the concrete. Water in admixtures and water used to dilute admixtures to aid in their addition to loads should be included in the determination of w/cm . Specifications that require the use of several chemical admixtures may require revisions. Revisions should be addressed during the bidding process. For example, depending on the number, type, and dosage of

chemical admixtures, it might be necessary to increase the maximum allowed truck mixer drum revolutions and the maximum allowed slump.

The concrete producer, with assistance from technical representatives of admixture suppliers, should determine the batching order or sequence for incorporating admixtures. If the batching and mixing process produces concrete with slumps and air contents that do not comply with specification requirements, it will require an adjustment. This adjustment can be done at the concrete plant, the jobsite, or both. This may require additional HRWRAs, air-entraining admixtures, or both, be added to concrete in a truck mixer drum. Subsequent mixing time is related to load size, drum condition, and slump. Slump should be sufficiently high to facilitate mixing and, as a result, improve concrete uniformity. In the absence of experience suggesting otherwise, consider batching chemical admixtures in the following order or sequence:

- a) Air-entraining admixtures
- b) Water-reducing admixtures (Type A or D)
- c) Retarding admixtures (Type B)
- d) Accelerating admixtures (Type C)
- e) High-range water-reducing admixtures
- f) Permeability-reducing admixtures
- g) Shrinkage-reducing admixtures
- h) Corrosion-inhibiting admixtures
- i) Viscosity-modifying admixtures

And if, subsequently, it is necessary to increase slump, air, or both consider:

- a) High-range water-reducing admixtures
- b) Air-entraining admixtures

3.8—Chapter reference chart

Although several chapters in this report are organized to address the use of one or more admixtures for a specific type of concrete behavior, much of the report is categorized by generic classifications of admixtures. For assistance, refer to Table 3.8 as a chapter reference guide to admixture types and their applicability to concrete performance, use, and exposure of interest.

CHAPTER 4—SUSTAINABILITY

4.1—Sustainability of chemical admixtures

The sustainability of building materials is an important component of sustainable construction. All materials contribute to the environmental impact of a structure and are included in the life cycle assessment (LCA) used to measure the sustainability of a structure. The product category rule (PCR) for concrete details the information required for an environmental product description (EPD) (Lemay 2012; Mitchell 2014). The cutoff level for inclusion in the PCR is 1 percent of mass. The draft PCR makes this statement regarding admixtures:

While the use of most chemical admixture will fall well within the 1 percent of mass, the energy impacts of chemical admixture production are not

readily available. Additional research is required to verify this fact. Current industry practice is to omit the impacts of chemical admixtures.

Quantifying the impact of such a small mass of material under current industry practices would not produce meaningful data and should, therefore, not be of concern to the concrete designer or user. However, should the admixture content of concrete exceed the 1 percent by mass level, it is appropriate to request an EPD from the admixture manufacturer. The development of future guidelines might require inclusion of all admixtures in the PCR and subsequent EPD.

4.2—Use of chemical admixtures in sustainable construction

The use of chemical admixtures can beneficially influence the environmental impact of concrete construction in a number of areas. These include, but are not limited to:

a) During concrete production:

i. Reduce the amount of natural resources used in the manufacture of concrete or concrete products by:

1. Reducing the amount of potable batch water used through the use of normal-, mid-, and high-range water reducers (Chapter 6)

2. Reducing the amount of cementitious material used (Chapter 6)

3. Reusing fresh stabilized concrete or concrete wash water through the use of extended set-control admixtures (Chapter 9)

4. Reducing the duration time and temperature required to heat/steam cure precast/prestressed concrete (Chapters 6, 7, and 20)

ii. Reduce or eliminate process-water-treated discharge through application of extended set-control admixtures during truck washout, enabling the gray water thus produced to be used in concrete production (Chapter 9)

b) During construction:

i. Reduce the initial emissions footprint and embodied energy of concrete materials either by:

1. Reducing the amount of cement needed, or allowing alternative cementitious materials with lower environmental signature, while maintaining the same or improved concrete properties (Chapters 6 and 20)

2. Reducing the actual volume of concrete needed through application of admixtures to achieve higher strength, with benefit both in cementitious materials and aggregate volumes; this requires alternate structural design (Chapter 20)

ii. Reducing emissions and energy consumption through faster concrete truck discharge rates and faster concrete placements (Chapter 20)

iii. Reducing the labor involved in concrete placement, with resulting reduction of environmental impact due to reduced labor support facilities (Chapter 20)

iv. Speeding construction, with reduced environmental footprint of commuting for all construction labor; in infrastructure applications, avoiding the environmental impact of traffic control and delay of the public (Chapter 7)

Table 3.8—ACI 212.3R chapter reference guide to concrete requirements and exposures

		Chapter number and title																		
		5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21		
Concrete requirements exposures		Air-entraining admixtures	Normal, mid- and high-range water reducers	Accelerating admixtures	Set-retarding admixtures	Extend set-control admixtures	Workability-retaining admixtures	Viscosity- and rheology-modifying admixtures	Shrinkage-reducing admixtures	Corrosion-inhibiting admixtures	Lithium admixtures to reduce ASR	Permeability-reducing admixtures	Miscellaneous admixtures	Admixtures for flowing concrete	Admixtures for self-consolidating concrete	Admixtures for very cold weather concrete	Admixtures for very high-early-strength concrete	Admixtures for pervious concrete		
Constructibility attributes required	Workability	□	■											■	■					
	Flowability		■					□						■	■					
	Finishability		■																	
	Self-consolidating		□					■							■					
	Cohesive	□						■				□								
	Fast-setting		□	■			□									□	□			
	Slow-setting				■	■														
	High early strength		□	□													■			
	Bleeding control	□	□						■											
Special construction conditions	Hot weather				■															
	Cold weather			■												□				
	Sub-freezing weather	□	□	□												■				
	Underwater							■				□								
	Pumped		■					■												
	Long haul/long placement		□		□	■	□													
	Long pump distance		□		□	■	□													
	Fast-track construction		□	□													■			
	Congested reinforcing bar													□	■					
Special engineering properties/ applications	Difficult access to consolidate					□								□	■					
	Extruded concrete					□		■												
	High strength		■																	
	High modulus of elasticity		■																	
	Low shrinkage		□						■			□								
	Low curling		□						■											
	Reduced cracking		□						■											
	Reduced creep								■											
	Damp-proof/low absorption		□						□				■							
Special environmental conditions in service	Low permeability		■									■								
	Extended joint spacings								■											
	Lightweight/cellular	□											■							
	Freezing/thawing exposure	■										□								
	Chloride exposure	□	■							■		■								
	Salt scaling	■	■									□								
	Sulfate exposure		■									■								
Special aesthetic considerations	Water exposure		□									■								
	Alkalis with reactive aggregate									■		□								
	Acidic/sewage systems											□								
	Blemish-free								□						□					
Special concrete/structure/element considerations	Architectural surfaces														■					
	Enhanced flatwork finish		■																	
	Minimal cracking		□						■											
	Paving	■	■															□		
	Porous paving																	■		
	Mass concrete		■		□	□														
	Steel trowel floor	□*	■	□	□								□							
	Superflat floors		□						□				□							
	Flowable fill	□																		
Other	Semi-dry concrete												■							
	Sprayed concrete (shotcrete)												■							
	Recycling fresh concrete					■														
	Wash water recycling					■														
	Reclaimer optimization					■														

*Refer to cautions for air in steel trowel floor.

■: The chapter directly above has information that is highly relevant to the concrete requirement or exposure listed directly to the left.

□: The chapter directly above has information that is a lower degree of relevance between the chapter and corresponding concrete requirement/exposure.

- v. In cold weather applications, reducing or eliminating the energy associated with adjusting temperature required to produce normal setting characteristics (Chapter 7)
- c) Structure in use:
 - i. Extending the service life of concrete structures through various durability-enhancing admixtures
 - ii. Permitting specialty design to maximize thermal mass benefits of concrete
 - iii. Facilitating pervious concrete production for storm water runoff control
 - iv. The use of coloring admixtures to lighten the color of concrete to reduce heat-island effect and improve reflectivity

It is beyond the scope of this section to discuss all of these applications in detail.

The lifecycle assessment (LCA) of a structure should account for the contribution of concrete to the sustainability of the structure. In general terms, it can be assumed that extending the in-service life of concrete by maximizing the durability of the concrete and optimizing the use of concrete's thermal mass will have the greatest impact on more sustainable construction. The calculation of LCA is a developing technology; some of the environmental impacts are currently difficult to precisely quantify. Table 4.2 gives a general overview of ways in which various admixture types can achieve beneficial environmental impact. Because this is not a comprehensive overview, the quantitative benefits are likely to vary widely in differing situations.

In many applications, admixtures have achieved such widespread use, driven by economic reasons, that these sustainability benefits are not recognized. In a majority of the cases, savings in cement reduction will well offset the cost increase due to use of high-range water reducers (HRWRs) instead of a water reducers. In other applications, however, where admixtures are not used, consideration of the sustainability impact could make their use more appropriate. For example, using a high-range water-reducing admixture (HRWRA) instead of a conventional water-reducing admixture can reduce the cementitious material required for equal strength as much as 10 percent, yet because the incremental admixture cost exceeds the dollar value of the cement saving, no change is made. If sustainability was considered, the decision could change. Reducing the quantity of cementitious material at the same w/cm has also been shown to improve transport properties of the concrete (Buenfeld and Okundi 1998; Dhir et al. 2004).

CHAPTER 5—AIR-ENTRAINING ADMIXTURES

5.1—Introduction

An air-entraining admixture is one that causes the development of a system of microscopic air bubbles in concrete, mortar, or cement paste during mixing, usually to increase resistance to freezing and thawing and improve workability. The entrained air-void system is distinct from air voids physically entrapped in concrete during placement and consolidation. Air-entraining admixtures function by stabilizing the

air voids folded into the concrete during the mixing process. Air entrainment should always be required when concrete will be subjected to freezing and thawing and where the use of deicing chemicals is anticipated. Highway pavements, parking structure slabs, bridge decks, garage floors, driveways, curbs, and sidewalks located in cold climates will probably be exposed to such conditions. Specified air content should be achieved by batching an air-entraining admixture and measuring the air content of fresh concrete with air meters. Density (unit weight) tests are often conducted as part of a quality assurance program (ASTM C138/C138M; Roberts 2006). The resistance of concrete to freezing and thawing is affected by placing, consolidating, finishing, and curing procedures; therefore, acceptable construction practice in these respects should be followed (ACI 201.2R; ACI 302.1R; ACI 304R; ACI 308R; ACI 309R).

Extensive laboratory testing and long-term field experience have demonstrated conclusively that portland-cement concrete should contain at least a minimum amount of properly entrained air to resist the action of freezing and thawing (Cordon 1946; Blanks and Cordon 1949; Mather 1990). The process by which air is entrained in concrete and the mechanism by which such air entrainment prevents damage due to freezing and thawing is beyond the scope of this report, but is summarized in various textbooks (Powers 1968; Mindess and Young 1981; Mehta and Monteiro 1993) and in ACI 201.2R. More detailed discussions can be found in research papers (Cordon 1966; Litvan 1972; MacInnis and Beaudoin 1974; Powers 1975; Whiting and Nagi 1998).

5.2—Materials for air entrainment

Many materials can function as air-entraining admixtures. Those materials, however, that are used to create cellular concrete by creating gas bubbles inside the concrete are not acceptable air-entraining admixtures (ACI 523.1R). Examples of these materials include hydrogen peroxide and powdered aluminum.

5.2.1 Water-soluble compounds—Water-soluble, air-entraining admixtures are formulated using salts of wood resins, synthetic detergents, salts of petroleum acids, salts of proteinaceous acids, fatty and resinous acids and their salts, and organic salts of sulfonated hydrocarbons. Not every material that fits the preceding description, however, will produce a desirable air-void system. All air-entraining admixtures should meet the requirements of ASTM C260/C260M. Most commercial air-entraining admixtures are in liquid form, although a few are powders, flakes, or semi-solids. The proprietary name and the net quantity in pounds (kilograms) or gallons (liters) should be indicated on the containers in which the admixture is delivered.

5.2.2 Solid materials—Solid particles that have a high internal porosity and suitable pore size have been added to concrete and appear to act like air voids (Ramachandran 1995). These particles can be hollow plastic spheres, crushed brick, expanded clay or shale, or spheres of suitable diatomaceous earth. Research has indicated that when using inorganic particulate materials, the optimum particle size should be 0.01 to 0.05 in. (300 μ m to 1,250 μ m) (No. 16 to 50 sieve

Table 4.2—Admixture types and their environmental impact

Admixture type	Effect on concrete	Sustainability impact—concrete production	Sustainability impact—initial construction	Sustainability impact—life cycle
Extended set-control admixtures	Can provide extreme retardation, yet with good set predictability can stop hydration in fresh concrete enabling reuse; can stop hydration of cement in wash-out applications.	Enable reuse of returned concrete. Enable recycling of cement in wash out while retaining its cementitious properties; enable long delivery times so that temporary batch plants do not need to be erected in environmentally sensitive areas.	Allows full load delivery in slow placement situations where normally short loads would be needed; eliminating second truck cycle environmental footprint.	—
Water-reducing and mid-range water-reducing	Less water, resulting in less cement for equivalent strength.	Less water consumed per volume of concrete.	Lower carbon footprint through reduction in cementitious materials.	—
High-range water-reducing	Less water, resulting in less cement for equivalent strength. Higher slump at equal water.	Less water consumed per volume of concrete.	Substantially lower carbon footprint through reduction in cementitious materials. Reduction in construction labor, reducing related carbon footprint.	—
Accelerating admixtures	Accelerate hydration, especially in cold weather.	Reduce or eliminate need for hot water or heated aggregates.	Reduce heating forms and reduce heated enclosures.	—
Admixtures for self-consolidating concrete	Much higher workability at equal water.	Faster truck discharge and placement rates.	Markedly reduced placement labor and related carbon footprint.	—
Air-entraining	Low cement content mixtures; air replaces water volume, giving water reduction. Stable air void distribution, lower permeability.	—	Lower carbon footprint through reduction in cementitious materials and in some cases sand.	More durable concrete-enhancing service life.
Corrosion-inhibiting	Delays onset of reinforcing steel corrosion in salt environments.	Some types promote early strength, reducing elevated curing requirements.	Eliminates the carbon footprint of epoxy-coated reinforcing.	Extends service life.
Permeability-reducing	Decreased permeability, longer time to corrosion.	—	Eliminates need for post-placement applied barrier, compressing the construction schedule and associated carbon footprint.	Extends service life.
Shrinkage-reducing	Reduces cracking due to shrinkage; can allow longer joint spacing in some instances.	—	Extended joint spacing can allow faster construction, reducing labor and equipment use, and carbon footprint.	Crack reduction reduces ingress of aggressive species, extending service life.
Admixtures for coloring concrete	Lighter-colored concrete.	—	—	Lower heat island effect in paved areas. Reduction in lighting load, for example, in parking garages.
Admixtures for pervious concrete	Facilitates placement, speed truck discharge, and improves raveling resistance.	More complete truck discharge reduces returned concrete.	Faster placement reduces truck idling time. Allows the use of alternate delivery and placement methods potentially lowering the carbon footprint.	Reduced storm water runoff, extend service life through better raveling control.

size). The total porosity of the particles should be at least 30 percent by volume, and the pore-size distribution should be between 0.05 and 3 μm (Gibbons 1978; Sommer 1978). Inclusion of such particulates in the proper proportion has produced concrete with resistance to freezing and thawing in laboratory tests using ASTM C666/C666M (Litvan and Sereda 1978; Litvan 1985). Admixtures containing microspheres are reported to have a resilient, tough, flexible shell similar to entrained air voids, providing stress relief zones during the expansion of freezing water within concrete (Bury et al. 2014). Admixtures containing particulate materials that provide resistance to cyclic freezing and thawing may have the ability to provide a stable void system. Once

added to fresh concrete, changes in mixing procedure or time; changes in temperature, workability, or finishing procedures; or the addition of other admixtures, fly ash (ACI 232.2R), or other cementitious materials such as ground slag (ACI 233R) may not change the void system created by the particulate admixture. This may not be the same case with conventional air-entraining admixtures.

5.3—Mechanism of entrained air

5.3.1 Entrained air-void systems—Improvements in resistance to freezing and thawing are due to the presence of minute air bubbles dispersed uniformly through the cement paste portion of the concrete that provide relief from the pres-

sure of freezing water. Because of the bubbles' size, there are billions of bubbles in each cubic meter of air-entrained concrete. To provide adequate protection with a relatively low total volume of void space, the bubbles should be small (0.0004 to 0.004 in. [10 to 100 μm] in diameter).

The cement paste in concrete normally is protected against the effects of freezing and thawing if the spacing factor (Powers 1949) does not exceed 0.008 in. (0.20 mm), as determined in accordance with ASTM C457/C457M. This is generally achieved when the surface area of the air voids is greater than 600 in.²/in.³ (24 mm²/mm³) of air-void volume, and the number of air voids per 1 in. (25 mm) of traverse are 1.5 times greater than the numerical value of the percentage of air in the concrete (Hover 1994). Many investigators report that the addition of some high-range water-reducing admixtures (HRWRAs) to air-entrained concrete increases the spacing factor and decreases the surface areas of the air-void systems beyond the accepted limits (Tynes 1977; Mather 1979; Schutz 1978; Whiting 1979; Litvan 1983). Numerous studies, however, indicate that such admixtures do not reduce the freezing-and-thawing resistance of concrete (Kobayashi 1981; Malhotra and Malanka 1979; Mather 1979; Philleo 1986).

The air content and the size distribution of air voids produced in air-entrained concrete are influenced by many factors. Most importantly, they are influenced by the nature and quantity of the air-entraining admixture, the nature and quantity of the constituents of the concrete, the type and duration of mixing employed, the consistency and slump of the concrete, and the kind and degree of consolidation applied in placing the concrete (Backstrom et al. 1958; Mielenz et al. 1958a,b). Admixtures react differently with varying concrete constituents, temperatures, slumps, and cements. Field evaluations are often beneficial because uniformity of air content throughout a project is essential. Field tests should be used to verify the uniform performance of the proposed air-entraining admixture. Therefore, the air-entraining admixture choice on a given project should be based on current information and recent field test data. Air content in hardened concrete is determined either by the linear traverse or point-count technique and generally is slightly lower than values obtained from tests of the fresh concrete (Carlson 1967; Reidenour and Howe 1975). The difference generally differs by less than two percentage points (Pinto and Hover 2001).

Newlon (1971) analyzed field data on cores taken from bridge decks and found that 22 of 26 samples were within 1.25 percentage points of the air content measured in the fresh concrete. When considerable amounts of entrapped air are present in core specimens, however, air contents, as determined by ASTM C457/C457M, can be up to 3 percentage points less than those determined by the pressure meter (Amsler et al. 1973). Occasionally, measured air contents in hardened concrete can be as much as twice those measured in as-delivered concrete. Explanations of this phenomenon include the incompressibility of very small (0.0002 in. [$<50 \mu\text{m}$] diameter) air voids (Hover 1989) and the transfer of air between small and large air bubbles

(Fagerlund 1990). Attempts to reproduce this phenomenon under controlled laboratory and field conditions have been unsuccessful (Ozyildirim 1991).

Air content readings should be verified on site by unit weight (density) tests. When unit weight buckets are not available, the use of air meter buckets to determine density, regardless of nominal maximum size of coarse aggregate, is preferable to not performing density tests. Concrete suppliers should determine the relationship between density and air content for various concrete mixtures, as explained in 5.10.3. Also, concrete cylinders should be weighed after demolding and before capping, and the weight recorded on strength test reports. This provides useful information relative to cylinder manufacture, density, yield, air content, and strength.

5.4—Selection and evaluation

To improve resistance to freezing and thawing, intentionally entrained air should have certain characteristics, as outlined in 5.3. An admixture that meets the requirements of ASTM C260/C260M may produce a desirable air-void system when recommended air contents are achieved. Improvements in resistance to freezing and thawing are due to the presence of minute air bubbles uniformly dispersed throughout the concrete. ASTM C260/C260M also sets limits on the effects of any given air-entraining admixture on bleeding, time of setting, compressive and flexural strength, resistance to freezing and thawing, and length change on drying of a hardened concrete mixture in comparison with a similar concrete mixture that contains a standard reference air-entraining admixture, such as neutralized thermoplastic resin. Acceptance testing should follow ASTM C231/C231M. ASTM C457/C457M can be used to determine the actual parameters of the air-void system in hardened concrete to provide greater assurance that satisfactory resistance to freezing and thawing is obtained.

5.5—Applications

Air-entrained concrete should be used wherever concrete contains absorbed moisture and is exposed to freezing and thawing, especially when deicing chemicals are used. Because air entrainment also improves the workability of concrete, it is particularly effective in lean mixtures and in various kinds of lightweight-aggregate concrete. Air entrainment is used in insulating and cellular concrete (ACI 523.1R), structural lightweight concrete, and normalweight concrete. Blisters and delaminations can occur when normalweight concrete with an air content above 3 percent receives a hard-troweled finish (ACI 302.1R; Bimel 1998).

No general agreement exists on the benefits of using air-entraining admixtures in the manufacture of concrete block (Farmer 1945; Kennedy and Brickett 1986; Kuenning and Carlson 1956). Air entrainment is used in some areas and specified in others. Air-entraining admixtures, however, are marketed specifically for zero- and low-slump concrete to produce a stable air-void system with proper bubble size and spacing.

Air entrainment is desirable in wet-process block made for the same purposes as in conventional concrete. The process

of pumping, spraying, and impinging on a surface limits the air content of in-place shotcrete to approximately 4 percent, in spite of higher air contents before pumping (Morgan 1991).

In dry-process shotcrete, using air-entraining admixtures is questionable because there is no mixing to develop an acceptable air-void system (Segebrecht et al. 1989). Nevertheless, air-entrained dry-process shotcrete exhibits excellent durability when exposed to freezing and thawing (Litvin and Shideler 1966; Gebler 1992). ACI 506R recommends the air-entraining admixture be introduced to the mixture at the nozzle in combination with the mixing water.

5.6—Dosage

The dosage required to achieve the desired air content should be determined by trial mixtures, starting from the manufacturer's recommendations or from experience. For any given set of conditions and materials, the amount of air entrained is roughly proportional to the amount of admixture used. Proper air content problems are particularly acute during hot weather. The batching order of admixtures may affect the amount of air entrained for a set dosage of air-entraining admixture, and recommended batching sequences are addressed in 3.7.

5.7—Proportioning concrete

5.7.1 Adjustments in proportions—Air entrainment changes the properties of fresh concrete. Mixture designs should be proportioned in accordance with ACI 211.1, ACI 211.2, or other method. Air-entrained concrete will require an adjustment in proportions to achieve the required yield as compared to non-air-entrained concrete. The increased volume of air will require an equal volume reduction of aggregate, typically sand. Air entrainment may reduce water, particularly at low cementitious contents, and often improves workability compared to non-air-entrained concrete at the same slump. At high cementitious material contents, air-entrained concrete may become sticky and difficult to finish. Workability, finish, and setting time of the proposed mixture design can be verified with a successful placement on site. Air entrainment also reduces bleeding and the accumulation of laitance or weak material at the surface of a lift. Air entrainment usually reduces the compressive strength of hardened concrete, as addressed in 5.9.2. A proper air-void system should be provided, while excessive amounts of entrained air should be avoided. A maximum air content of 3 percent should be specified for concrete receiving a steel-troweled finish. Air contents above that have resulted in significant blisters and slab delaminations (ACI 302.1R).

5.7.2 Effects of materials and proportions—Many factors can influence the amount of air entrained in concrete (Whiting 1983; Whiting and Nagi 1998). The dosage of an admixture required to obtain a given air content varies depending on the particle shape and grading of the aggregate. Organic impurities in the aggregate usually decrease the air-entraining admixture requirements. Hardness of water generally does not significantly affect the air-entraining admixture requirements (Wuerpel 1946). As concrete temperature increases,

higher dosages of air-entraining admixtures are required to maintain the desired air content.

Increasing the cement content or fineness decreases the amount of air entrained by a given amount of an admixture. Thus, larger amounts of air-entraining admixture are required in concrete containing high-early-strength Type III cement or portland-pozzolan cement (Type IP). High-alkali cements require a smaller amount of air-entraining admixture to obtain a given air content than do low-alkali cements. Similarly, increasing the amount of finely divided materials in concrete (by using fly ash, slag, or other pozzolans; carbon black or other pigments; or bentonite) also decreases the amount of air entrained by a fixed dosage of an admixture. An air-entraining admixture generally produces more air when calcium chloride is used as an accelerator. This effect is more pronounced with certain water-reducing admixtures where the amount of air-entraining admixture required to produce a given air content can be reduced by one-third or more (Dodson 1990). A satisfactory air-void system is required. Therefore, if the mixture constituents have not previously proven to develop a satisfactory air-void system, they should be verified.

The proportioning of air-entrained concrete is similar to that of non-air-entrained concrete. Methods of proportioning air-entrained concrete should follow the procedures of ACI 211.1, ACI 211.2, or other method. These procedures incorporate the reduction in water and fine aggregate permitted by the improved workability of air-entrained concrete. The highest amount of air per unit of air-entraining admixture is developed within the 4 to 7 in. (100 to 175 mm) slump range. Within this slump range, as the w/cm is increased, air contents can increase, but the required characteristics of the air-void system might not be maintained (Dolch 1971).

5.8—Effects on fresh and hardening concrete

5.8.1 Effect on fresh concrete—Air entrainment in properly proportioned concrete could increase workability in low or moderate contents of cementitious materials. Air entrainment reduces segregation and bleeding, which helps to prevent the formation of pockets of water beneath coarse aggregate particles and embedded items such as reinforcing steel.

A properly air-entrained concrete would reduce bleeding and segregation characteristics and can improve pumpability. Air entrainment will not affect the setting time of the mixture. Air-entrained concrete may exhibit increased surface crusting and plastic cracking when placed in conditions of high temperature, low humidity, and wind due to reduced rate and quantity of bleeding.

5.8.2 Effect of mixing—The amount of air entrained varies with the type and condition of the mixers. Mixers become less efficient as the blades become worn or when hardened material is allowed to accumulate in the drum and on the blades. The air content may also change if there is a significant variation in batch size for a given mixer, especially if the batch size is different from the rated capacity of the mixer. Adams and Kennedy (1950) found that for various laboratory mixers, air content increases with capacity.

4 percent to as much as 8 percent as the batch size was increased from 40 to 100 percent of rated mixer capacity.

Laboratory studies (Bloem and Walker 1946) have shown that the amount of entrained air increases with mixing time up to a maximum value, beyond which it slowly decreases. The air-void system, as characterized by a specific surface and spacing factor, usually is not harmed by prolonged mixing. If more water is added to achieve the desired slump, the air content should be checked because some adjustment may be required. Adding water without complete mixing can result in nonuniform distribution of air and water within the batch. Air void clustering could occur (Kozikowski et al. 2005). Refer to ACI 304R for further details.

5.8.3 Effect of transporting and consolidation—The methods used to transport concrete after mixing, such as pumping, can affect both the amount and quality of air in the concrete. There are reports that pumping could reduce the air content in concrete (Hover 1989; ACI 304.2R). Some admixtures, however, result in an increase in the air content during pumping (Burg 1985). The increase is apparently caused by the increased shearing action imposed by the screw that moves the concrete from the hopper into the pump cylinder.

The type and degree of consolidation used in placing concrete can reduce air content. Vibration applied to air-entrained concrete removes air as long as the vibration is continued (Backstrom et al. 1958); however, laboratory tests have shown that concrete's resistance to freezing and thawing is not reduced by moderate amounts of vibration. Stark (1986), however, has shown that extended vibration, particularly at high frequencies, can significantly reduce this resistance and disrupt the smaller bubbles.

5.9—Effects on hardened concrete

5.9.1 Freezing-and-thawing cycles—Properly proportioned air-entrained concrete is resistant to freezing-and-thawing cycles after achieving 4000 psi (27.6 MPa).

5.9.2 Compressive strength—Air entrainment reduces the compressive strength of hardened concrete, particularly with moderate to high cementitious material contents. Reduction is approximately 5 percent for each percent of entrained air; however, the rate of reduction of strength increases with higher amounts of air. Adding entrained air reduces the water content required to achieve the specified slump. The result in w/cm can partially offset the reduction of strength. This is particularly true of lean cementitious content concretes, concretes that contain a large maximum-size aggregate, or both. In these cases, air entrainment could cause only a small decrease in strength, or possibly a slight increase in strength.

5.9.3 Flexural strength—Air-entrained concrete with the same w/cm shows a slight decrease in flexural strength (Mailvaganam 1984; Departments of the Army and the Air Force 1987).

5.9.4 Permeability—Air-entrained concrete with a w/cm of 0.45 or less will reduce permeability by intersecting internal capillaries that can provide ingress for liquids (Lukas 1981).

5.10—Quality assurance and batching

5.10.1 Benefits of air entrainment—The full benefits of air-entrained concrete can only be realized when the mixture design provides consistent air contents that should be checked and verified in accordance with the recommendations of ACI SP-2 and ACI 311.4R. Proper air content in the hardened concrete is the key requirement. Air losses due to pumping, handling, transportation, and consolidating are not detected by air content tests performed at the mixer (ACI 309R). For control purposes, samples for determining air content should be taken directly from concrete at the point of deposit (ACI 301). The pumping process should eliminate freefall by a loop or slight curve in the line. When air loss between delivery and point of deposit becomes consistent, air content tests may be made at the point of delivery. Proper air content in the hardened state is the goal.

5.10.2 Air control tests—Air content tests of concrete should be made at regular intervals or whenever there is a reason to suspect a change in air content. Properties of the concrete-making materials, proportioning of the concrete mixture, and all aspects of mixing, handling, and placing should be maintained as constant as possible to ensure that the air content will be uniform and within the range specified for the work. Too much air may reduce strength without a commensurate improvement in durability, whereas too little air will fail to provide desired durability and workability.

5.10.3 Test methods—In general, air content tests are taken each time compressive test specimens, flexural test specimens, or both, are taken and at any other time so designated by the purchaser. Unit weight tests are recommended in addition to air meter tests to ensure that all the entrained air is recorded. Sometimes air meters do not detect the smaller entrained air bubbles. A chart indicating air contents versus unit weights can be established by the testing agency and be kept on site to quickly detect deviations from the specified air content envelope.

5.10.4 ASTM standards—There are three standard ASTM methods for measuring the air content of fresh concrete:

- 1) The gravimetric method: ASTM C138/C138M
- 2) The volumetric method: ASTM C173/C173M
- 3) The pressure method: ASTM C231/C231M

The pressure method is not applicable to lightweight concrete. The chase air indicator (Grieb 1958), which is an adaptation of the volumetric method, has not been standardized and should not be used to determine compliance with specification limits. The ASTM methods measure only air volume and not the air-void characteristics. While the spacing factor and other significant parameters of the air-void system in hardened concrete have traditionally been determined only by microscopic methods such as those described in ASTM C457/C457M, methods have been developed that determine air-void parameters of fresh concrete (Marsh 2015; Wojakowski 2003; Whiting 1993).

5.10.5 Batching—To achieve the greatest uniformity between batches of a concrete mixture, water-soluble air-entraining admixtures should be added to the mixture in the form of solutions rather than solids. Generally, only small quantities of air-entraining admixtures are required, approximately 0.05

percent of active ingredients by mass of cementitious materials—are required to entrain the desired amount of air. If the admixture is in solid or semisolid forms, a solution should be prepared before use, following the recommendations of the manufacturer.

CHAPTER 6—NORMAL, MID-, AND HIGH-RANGE WATER-REDUCING ADMIXTURES

6.1—Introduction

Water-reducing admixtures reduce the water requirements of a concrete mixture for a given slump. Water-reducing admixtures can be formulated for normal, retarding, and accelerating setting characteristics. Refer to [Chapter 7](#) for more information about water-reducing and accelerating admixtures and [Chapter 8](#) for water-reducing and set-retarding admixtures. Admixtures formulated for normal water reduction and normal setting characteristics always meet the requirements of [ASTM C494/C494M](#), Type A.

These admixtures are frequently formulated with a water-reducing retarding component, offset by the addition of an accelerating component to achieve the required neutral set. Water reduction, therefore, is frequently limited to 10 percent or less before retardation prevents higher dose. For this reason, higher doses of Type A water reducers are sometimes used in hot weather, but care should be taken because the accelerating component may have the effect of accelerating the aluminate phase in the cement, which can result in slump loss and sometimes failure to gain early strength.

Water-reducing admixtures formulated for normal setting characteristics at higher dosages, using the aforementioned approach, that also often include the addition of nonionic surfactants to aid water reduction and workability, are known as mid-range water-reducing admixtures (MRWRAs) ([Nmai et al. 1998a](#)). Although there is no ASTM classification for MRWRA, these admixtures should show compliance with ASTM C494/C494M Type A water-reducing admixtures, and sometimes meet ASTM C494/C494M Type F high-range water-reducing admixtures (HRWRAs). HRWRA could achieve up to 40 percent water reduction at higher dosages, such as 0.8 percent of cementitious materials. A Type A water-reducing admixture could retard the set of concrete at a dosage higher than 0.2 percent of cementitious materials. MRWRA could provide up to 12 percent water reduction without significantly delaying the setting time of the concrete. Conventional water-reducing admixtures cannot do this because they cause excessive retardation at higher dosages. Normal-setting HRWRAs must show compliance with the requirements of ASTM C494/C494M Type F HRWRAs. Normal-setting HRWRAs differ from conventional water-reducing admixtures because they do not significantly delay the hydration process until much higher dosages are used (up to 0.75 percent by mass of cement). Therefore, HRWRAs can provide significantly greater water reduction without excessive air entrainment or retardation. At lower concentrations, they impart the same water reduction and strength benefits as other water-reducing admixtures.

6.2—Materials

6.2.1 Classification—Water-reducing and set-control admixtures should meet the applicable requirements of ASTM C494/C494M, which defines seven types:

- 1) Type A—Water-reducing admixtures
- 2) Type B—Retarding admixtures ([Chapter 8](#))
- 3) Type C—Accelerating admixtures ([Chapter 7](#))
- 4) Type D—Water-reducing and retarding admixtures
- 5) Type E—Water-reducing and accelerating admixtures
- 6) Type F—Water-reducing, high-range admixtures
- 7) Type G—Water-reducing, high-range, and retarding admixtures

ASTM C494/C494M gives detailed requirements for water requirement, setting time, flexural and compressive strength, drying shrinkage, and resistance to freezing and thawing. Admixtures showing compliance with ASTM C494/C494M Types F and G may also be covered by [ASTM C1017/C1017M](#) as Type I and Type II ([Chapter 7](#)). ASTM approved a Type S (specialty admixture) designation (ASTM C494/C494M) that includes admixtures not covered by other ASTM standards.

The specific effects of water-reducing admixtures, however, vary with different cements, addition sequences, changes in w/cm , mixing temperature, ambient temperature, and other site conditions. Most water-reducing admixtures perform considerably better than the minimum requirements of ASTM C494/C494M regarding water reduction and compressive strength. The dosage at which a water-reducing admixture meets the performance requirements in ASTM C494/C494M with a specific cement may be higher or lower when tested with different concrete ingredients and proportions.

6.2.2 Compositions—Materials generally available for use as water-reducing admixtures fall into one of seven general categories of compounds. Formulations can include, but are not limited to, compounds from more than one category:

- 1) Lignosulfonic acids and their salts and modifications and derivatives of these
- 2) Hydroxylated carboxylic acids and their salts and modifications and derivatives of these
- 3) Carbohydrate-based compounds such as sugars, sugar acids, and polysaccharides
- 4) Salts of sulfonated melamine polycondensation products
- 5) Salts of sulfonated naphthalene polycondensation products
- 6) Polycarboxylates
- 7) Other materials that can be used to modify formulations, including nonionic surface-active agents; amines and their derivatives; organic phosphonates, including zinc salts, borates, phosphates; and certain polymeric compounds, including cellulose-ethers, silicones, and sulfonated hydrocarbon acrylate derivatives.

6.3—Selection and evaluation

If adequate information is not available, tests should be done to evaluate the effect of the water-reducing admixture on the properties of concrete made with job materials under the anticipated ambient conditions and curing procedures. Tests of water-reducing admixtures should indicate

their effect on the following properties of concrete, insofar as they are pertinent to the job:

- a) Water requirement
- b) Air content
- c) Slump
- d) Bleeding and possible loss of air from the fresh concrete
- e) Setting time
- f) Compressive and flexural strength at 28 days, or the specified age of the concrete
- g) Required strength development
- h) Resistance to freezing and thawing
- i) Drying shrinkage

When water-reducing admixtures are evaluated in laboratory trial batches before use, a series of mixtures should be planned to provide the necessary information. The mixtures need not follow ASTM C494/C494M procedures. The trial mixtures should be made with the same cementitious materials and other concrete-making materials that will be used on the project and as close to job conditions as possible. Temperature is particularly important to setting time and early strength development. Because different phases of the cement are affected differently by temperature, odd behavior, such as slower set at higher temperatures, is possible (Cost 2006). Therefore, it is very important to test at the highest anticipated temperature. Air content and setting time of field concrete can differ considerably from that of laboratory concrete with the same materials and mixture proportions. The action of a water-reducing admixture may differ in a truck mixer from that seen in a laboratory mixer. The admixture dosage may have to be adjusted to get the same performance in the truck. In most cases, high-range water-reducing admixtures (HRWRAs) will be more efficient when mixed in a truck, and the dosage will be reduced. All parties should be alert to this possibility at the start of a job and ready to adjust the amounts of materials, particularly air-entraining admixtures, to achieve the specified properties of the concrete at the project site.

6.4—Applications

Water-reducing admixtures lower the w/cm and are used to produce higher strength and increased durability, obtain a required strength at lower cement content, increase slump without an increase in water content, or a combinations of these objectives. They also may improve the properties of concrete containing aggregates that are harsh, poorly graded, or both, or may be used in concrete that will be placed under difficult conditions. Water-reducing admixtures are useful when placing concrete by pump or tremie.

Mid-range water-reducing admixtures (MRWRAs) are typically used to produce concrete within a slump range from 75 to 200 mm (3 to 8 in.). They are beneficial to improving the finishing and pumping characteristics of concrete.

High-range water-reducing admixtures (HRWRAs) can produce large reductions in the water content of concrete—over 40 percent reduction in some cases. While such high water reduction is possible, especially in precast operations where placement time is quick, proceed with caution to avoid issues such as slump loss and retardation. HRWRAs are often used

in the production of high-strength concrete, precast/prestressed concrete, architectural concrete, parking and bridge structures, rapid-cycle high-rise projects, industrial slabs, and massive concrete structures. They are often used to produce flowing concrete with slump in excess of 8 in. (200 mm) (Chapter 17). Some HRWRAs can be used in conjunction with proper mixture proportioning and other materials to produce self-consolidating concrete (SCC) (ACI 237R) with slump flow values up to 30 in. (760 mm) (Chapter 18). HRWRAs have also been used to reduce cement content. Because the w/cm affects the concrete strength, the cementitious content can be reduced with a proportional reduction of the water content for equivalent or higher-strength concrete; this is due to increased cement efficiency, which results in cost savings. In mass concrete, low cement content is desirable because it lowers the temperature rise of the concrete, as detailed in 6.7.7. The addition of an HRWRA can reduce pump pressures up to 35 percent for normalweight concrete, and by 10 to 20 percent for lightweight concrete (Kasami et al. 1979).

The use of water-reducing admixtures can beneficially influence the environmental impact of concrete construction (Chapter 4) in a number of areas, including:

- a) Less water consumed per volume of concrete
- b) Substantially lower carbon footprint through reduction in cementitious materials
- c) Facilitate the use of higher quantities of supplementary cementitious materials (SCMs) and marginal aggregates
- d) Reduction in construction labor, reducing related carbon footprint
- e) Increase the service life of structures

6.5—Dosage

The expected performance of a given brand, class, or type of water-reducing admixture can be estimated from one or more of the following sources of information:

- a) Results from jobs where the admixture has been used under good field control, preferably using the same materials and under conditions similar to those anticipated
- b) Laboratory tests made to evaluate the admixture
- c) Technical literature and information from the manufacturer

The dosage of the admixture should be determined from information provided by one or more of these sources. Varying results can be expected with a given admixture due to differences in cements, supplementary cementitious materials (SCMs), aggregates, other materials, and weather conditions. In the production of high-strength concrete (above 6000 psi [41 MPa]), it is often beneficial to increase the dosage of the admixture. This usually provides extra water reduction and typically a delay in setting time and slow early strength gain. Concrete with slow early strength gain generally exhibits higher later strengths (Rixom and Mailvaganam 1999; ACI 363R).

Concrete containing certain types of high-range water-reducing admixture (HRWRA) may experience rapid slump loss. To overcome this, a second addition or redosing of the HRWRA can be used to restore the slump without any negative effects. Generally, more than two additions are as effective as a single dose (Carrasquillo and Carrasquillo

1986) because concrete could lose its workability faster. Redosing may result in lower air content as well, possibly up to 1 to 2 percentage points for each additional dose. When redosages are used, the concrete may have a greater potential for bleeding, segregation, and possible retardation of setting time. Therefore, trial mixtures should be conducted to determine the effects of redosing. If slump loss is a concern, the type of HRWRA should be reviewed. The period of required plasticity should be verified by placing the proposed mixture on the project. Products that increase efficiency, improve cohesiveness, and maintain workability for longer periods of time are available. These HRWRAs can be added at the batch plant rather than the jobsite, thereby reducing wear on truck mixers and lessening the need for ancillary equipment such as truck-mounted admixture tanks and dispensers.

6.6—Proportioning concrete

When a concrete mixture considered satisfactory in workability and finishing qualities is modified to incorporate a water-reducing admixture, the ratio of mortar to coarse aggregate by volume should remain the same. Changes in water, cementitious material, and air content are compensated for by corresponding changes in the content of fine aggregate—all on a solid or absolute volume basis—so that the volume of mortar remains the same. Procedures for proportioning and adjusting concrete mixtures are covered by ACI 211.1. Most water-reducing admixtures are water solutions. The water they contain becomes a part of the mixing water in the concrete and should be considered in the calculation of w/cm , if the added amount of water is significant. The volume of solids in the admixture is so small in relation to the batch size that it can be neglected.

Concrete proportioned for high-strength concrete using HRWRAs usually has a sufficiently high cement content to supply the fines required for good workability. This can be reportioned by making up the volume of water reduced by increasing the volume of coarse or fine aggregate equally. If trial mixtures are sticky, the volume of coarse aggregate should be increased, and that of the fine aggregate reduced. This usually results in a mixture that is easier to place and finish. In proportioning for high-range water-reduced concrete in the ready mixture environment, slump loss is a major consideration. Generally, greater success is achieved if the concrete is proportioned such that there is a measurable slump of at least 1/2 in. (12.7 mm) prior to the addition of the high-range water reducer.

6.7—Effects on fresh and hardening concrete

6.7.1 Water reduction—ASTM C494/C494M Type A water-reducing admixtures decrease the water required for the same slump concrete by at least 5 percent, and in some cases water-reducing admixtures decrease the water by up to 12 percent, as it is with mid-range water-reducing admixtures (MRWRAs). Concrete containing lignosulfonate or hydroxylated carboxylic acid salts reduce the water content by 5 to 10 percent for a given slump and cement content. ASTM C494/C494M Type F requires that normal-setting high-range water-reducing admixtures (HRWRAs) reduce

the water requirement at least 12 percent. Reductions of over 30 percent have been reported (Portland Cement Association 2009) and HRWRAs can be used to significantly increase slump without increasing water content. They may also be used to achieve a combination of these two objectives, which is a slump increase and reduction in water content.

As the cement content of a concrete mixture increases, the required dosage of an HRWRA, as a percentage by mass of cement, is reduced (Collepardi 1984). The effects of these admixtures are also dependent on the C_3A , C_3S , and alkali contents of the cement. Concrete made with cements meeting requirements for Type II and Type V cements require lower admixture dosages than concrete containing Type I or Type III cements. In some cases, a higher SO_3 content in the cement may be desirable when using HRWRAs because the SO_3 aids in lowering the interparticle attraction of the cement particles by an electrostatic mechanism producing a more uniform dispersion of the cement grains.

6.7.2 Air entrainment—Some water-reducing admixtures may entrain air. Lignosulfonates entrain air to various degrees ranging from 2 to 6 percent, although higher amounts have been reported (Tuthill et al. 1960). The air-entraining properties may be controlled by modifying formulations. As explained in 6.2.2, materials in Categories 4 and 5 usually do not entrain air, but materials in all seven categories may affect the air-entraining capability of both air-entraining cement and air-entraining admixtures. This is particularly true in the case of some HRWRAs. The entrained air can consist of large, unstable bubbles that contribute little resistance to freezing and thawing; therefore, the entrained air-void characteristics should be evaluated whenever there are questions about the concrete performance. Testing for resistance to freezing and thawing in the evaluation is prudent, as sometimes the concrete is still durable, even with spacing factors that exceed the accepted limits of 0.008 in. (0.20 mm). For more information on resistance freezing and thawing, refer to 6.8.3.

6.7.3 Workability—When comparing a concrete mixture without a water-reducing admixture of the same slump and air content, differences in workability are difficult to detect because no standard test exists. Howard et al. (1960) reported the use of the Kelly Ball detected increases in workability that was missed by the slump test. Rheometers are useful in determining workability, flowability, and viscosity (Ferraris et al. 2000). Concrete containing a water-reducing admixture, however, is less likely to segregate and sometimes has better flowability.

Water-reducing admixtures affect bleeding capacity in varying degrees. For example, unmodified admixtures in Category 2 (6.2.2) tend to increase bleeding, whereas their modifications and derivatives do not. Admixtures in Category 1 reduce bleeding and segregation in freshly mixed concrete, partly due to the air entrainment. High-range water-reducing admixtures derived from Categories 4, 5, and 6 decrease bleeding, except at very high slump.

6.7.4 Rate of slump loss—The rate of slump loss can be decreased by adding water-reducing admixtures. Because of slump loss, some HRWRAs can be

added at the jobsite. Working time can be extended with the use of one of the following:

- a) **ASTM C494/C494M** Type B retarding
- b) Type D water-reducing and retarding admixture
- c) Type G retarding HRWRA
- d) The addition of a workability-retaining admixture (Chapter 10)

The working time depends on many factors, including the HRWRA dosage, use of other chemical admixtures, cement characteristics, w/cm , concrete temperature, slump, and age of the concrete when the HRWRA is introduced. Some HRWRAs extend the time before slump loss, allowing batch plant addition and maintaining normal setting-time characteristics (Guennewig 1988; Collepardi and Corradi 1979).

6.7.5 Finishing—Some water-reducing admixtures and MRWRAs improve the concrete's finishing characteristics compared to concrete containing other types of water-reducing admixtures or none at all. This is beneficial where deficient aggregate properties or gradation result in finishing difficulties. At the high-water content reduction achieved with HRWRAs, finishing may become more difficult due to the decrease in bleeding, and surfaces may have a tendency to crust and promote plastic-shrinkage cracking. The surface can be kept from drying by fogging using an evaporation retarder or other procedures (ACI 308R). These treatments should be used with caution so that the surface durability is not adversely affected. Using a combination of HRWRA and an MRWRA to achieve both high levels of water reduction and enhanced finishing properties is common.

6.7.6 Time of setting—Normal-setting water-reducing admixtures are generally formulated with an accelerating component to produce a setting time within 1.5 hours of a reference mixture at normal dosage rates. These admixtures will also produce extended setting times when dosages increase beyond normal rates or temperatures fall. The combination of conventional water-reducing admixtures and MRWRAs could cause retardation. Normal-setting HRWRAs can be used at higher dosages without an appreciable increase in setting times; however, increasing dosages beyond normal rates could also result in setting-time delays. Accelerating admixtures can decrease or eliminate retardation. Retarding admixtures are not recommended for controlling false set. False set, which is generally caused by precipitations of gypsum from high sulfate conditions, caused by hemihydrate (plaster) formed from gypsum in the mill during grinding, can be made evident by water-reducing admixtures. This is because a false set could delay its onset, which occurs during mixing when it can be mixed out, to afterward where it can be seen. Frequently, this results in added water, which hurts the concrete quality. When this is encountered, it is frequently overcome by delaying the addition time of the admixture to the tail end of the batching process after the cement is wetted. This allows the gypsum precipitation to start before the cement encounters the admixture. Fast set, sometimes called flash set or admixture set, can also be related to water reducer use. Very active aluminates in the cement or supplementary cementitious materials (SCMs), which are marginally controlled by the sulfate

added to the cement in manufacture, may become too active in the presence of the admixture. This may be due to dispersion causing extra surface to be available, or to solubility effects. Delayed addition also tends to help in this situation, as it gives time for the sulfate present to dissolve (Sandberg and Roberts 2005; Roberts and Taylor 2007).

6.7.7 Heat of hydration—Within normal w/cm ranges, heat of hydration and adiabatic temperature rise are not reduced at equal cement contents with the use of water-reducing admixtures (Poole 2007). Acceleration or retardation can alter the rate of heat generation, which can change the early rate of temperature rise under job conditions. If the use of water-reducing admixtures permits a reduction in cement content, the heat generated is proportionally reduced.

6.8—Effects on hardened concrete

6.8.1 Strength—In addition to the strength increase due to reduction of w/cm , strength is further increased due to modification of the paste microstructure by the water-reducing admixture. Normal setting and accelerating type water reducers can increase the early strength of concrete. Later-age strength with a water-reducing admixture can increase by 20 percent or more at the same cement content. Cement contents can, therefore, be reduced without lowering 28-day strengths. When HRWRAs are used to decrease the w/cm , the 28-day compressive strength can increase by 25 percent or more. Because of their effectiveness in reducing w/cm , HRWRAs are helpful in producing concrete with compressive strengths greater than 6000 psi (41 MPa) at 28 days and are essential in achieving strengths that exceed 10,000 psi (69 MPa). Increases in flexural strength of concrete containing a water-reducing admixture are not proportionally as great as increases in compressive strength (Collepardi 1984).

6.8.2 Shrinkage and creep—The effect of water-reducing admixtures on shrinkage is complex, with at least three interacting effects. First, reduction in water tends to reduce shrinkage. Second, by dispersion and the resulting extra hydration, shrinkage due to the lower volume of reaction products than reactants, which is known as chemical shrinkage, is increased. Finally, because drying shrinkage depends on the surface tension in the capillary pores, the presence of surface active agents in the water reducer may have a shrinkage-reducing effect. The net impact will depend on the concrete materials, the nature of the water reducer, and if the product is used to reduce water or increase slump. Creep is reduced in proportion to the increase in the concrete strength.

6.8.3 Durability—When water-reducing admixtures are used to lower the w/cm , concrete permeability is decreased and strength increased to increase the concrete durability. Concrete treated with an HRWRA has a resistance to chloride penetration similar or slightly higher than that of nontreated concrete with a similar w/cm . When used to reduce the w/cm , HRWRAs increase the resistance of concrete to the ingress of chlorides, reducing the potential for corrosion (Lukas 1981; Gebler 1982; Swamy 1989).

6.8.4 Resistance to freezing and thawing—At equal water-cement ratios (w/c), water-reducing admixtures typically have little effect on resistance to freezing and thawing, including

deicer scaling, because the resistance is almost entirely a function of the air-void system in the hardened concrete. An improvement can result from a decrease in w/cm because of increased strength and density and reduced permeability, which allow the concrete to remain less than critically saturated in the presence of water while being tested.

A spacing factor of 0.008 in. (0.20 mm) or less is generally needed in hardened concrete to be resistant to freezing and thawing cycles when tested in accordance to [ASTM C666/C666M](#) and [ASTM C672/C672M](#). Some HRWRAs, however, cause air void spacing factors (L) higher than generally considered necessary to produce concrete that will resist damage from freezing and thawing. Concrete made with HRWRAs with spacing factors of 0.10 in. (2.5 mm) or higher, however, were found to be highly resistant to freezing and thawing in both laboratory and field conditions ([Perenchio et al. 1979](#); [Mather 1979](#); [Kobayashi 1981](#); [Okada et al. 1981](#); [Roberts and Scheiner 1981](#)).

6.9—Quality assurance and batching

Water-reducing admixtures should be batched and dispensed as liquids. When supplied as solids, they should be mixed with water to a suitable solution concentration following the manufacturer's recommendations. The density of admixtures mixed on site or applied as solutions should be determined and compared with the manufacturer's standards. Density can be determined easily and quickly with a hydrometer or volumetric flask. Determinations should be made at a standard temperature and recorded for future reference as part of the site quality-control program. Storage tanks for solutions should be clearly identified, and the solutions should be protected from contamination, dilution, evaporation, and freezing.

Quality-assurance procedures for concrete containing an HRWRA are an extension of procedures established for conventional concrete. For both types of concrete, established procedures should ensure that the following areas are adequately addressed:

- a) Personnel training, including ACI certifications applicable to the task and laboratory competence, including accreditation
- b) Selection of materials, including material compatibility
- c) Mixture proportions, including trial batches to demonstrate field performance
- d) Storage of materials
- e) Plant equipment, including concrete mixer efficiency and effectiveness
- f) Batching, measuring, and mixing of materials
- g) Delivery equipment
- h) Delivery coordination
- i) Placement, consolidation, and finishing
- j) Protection and curing
- k) Establishment of a quality-control and quality-assurance system ([ACI 311.4R](#); [ASTM E329](#))

It is sometimes necessary or desirable to determine if an admixture is similar to a previously tested material, or that successive lots of shipments are similar. Tests used to identify admixtures include solids content, density, infrared spectrophotometry for organic materials, chloride content,

and pH. Guidelines for determining the uniformity of chemical admixtures are given in [ASTM C494/C494M](#). Project inspectors may be instructed to sample deliveries of the admixture as part of the project quality control or quality assurance. Admixture users should become familiar with appearances and odors of the admixtures to prevent errors.

CHAPTER 7—ACCELERATING ADMIXTURES

7.1—Introduction

An accelerating admixture is 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. Accelerating admixtures purchased for concrete use should meet the requirements of [ASTM C494/C494M](#) for Type C (accelerating admixtures) or Type E (water-reducing and accelerating admixtures).

Accelerating admixtures are used to decrease setting time and increase early strength gain, particularly in cold weather, to expedite the start of finishing operations, reduce finishing time, and reduce the time required for proper curing and protection; as well as to increase the early-strength level to permit earlier form removal and decrease the overall construction time. Accelerators are normally used in conjunction with other recommended practices ([ACI 306R](#)) to counteract the effects of low temperatures. Quick-setting admixtures permit more efficient plugging of leaks against hydrostatic pressure and produce rapid setting of concrete placed by shotcreting.

Certain accelerating admixtures used in combination with high-range water-reducing admixtures (HRWRA) significantly lower the freezing point of concrete and allow concrete placement to 20°F (−7°C). These admixtures and their effects are discussed in detail in [Chapter 19](#).

7.2—Materials

Accelerating admixtures are divided into four groups:

- 1) Those that contain soluble inorganic salts
- 2) Those that contain soluble organic compounds
- 3) Quick-setting admixtures
- 4) Miscellaneous solid admixtures

Water-reducing and accelerating admixtures are often formulated with one or more of the compounds listed in [6.2.2](#) to produce the required water reduction. Several compounds have been shown to act as accelerators, with many of those listed in the following sections. Most commercially available accelerating admixtures for use in cast-in-place or precast concrete are based primarily on chlorides, nitrates, thiocyanates, and nitrites, either separately or combined.

7.2.1 Soluble inorganic salts—Studies ([Edwards and Angstadt 1966](#); [Roskopf et al. 1975](#)) have shown that a variety of soluble inorganic salts, including chlorides, bromides, fluorides, carbonates, thiocyanates, nitrites, nitrates, thiosulfates, silicates, aluminates, and alkali hydroxides, decrease the setting time of portland cement. Of these salts, calcium chloride is the most widely used because it is the most cost-effective. Research by [Grunewald](#) and [Tigart](#) has shown that inorganic accelerating admixtures

Table 7.2.1—Calcium chloride: amount introduced

Calcium chloride by mass of cement, percent	Solid form, percent		Liquid form, 29 percent solution*	Amount of chloride ion added, percent
	Dihydrate [†]	Anhydrous [‡]	L/100 kg (qt/100 lb)	
0.5	0.7	0.5	0.57 (0.6)	0.3
0.8	1.0	0.8	0.95 (1.0)	0.5
1.0	1.3	1.0	1.14 (1.2)	0.6
1.5	2.0	1.5	1.70 (1.8)	1.0
2.0	2.6	2.0	2.27 (2.4)	1.3

*A 29 percent solution often is the concentration of commercially used liquid forms of calcium chloride and is made of dissolving 0.45 kg (1 lb) dihydrate to make 0.95 L (1 qt) of solution.

[†]Commercial flake products generally have an assay of 77 to 80 percent calcium chloride, which is often close to dihydrate.

[‡]Commercial anhydrous calcium chloride generally has an assay of 94 to 97 percent calcium chloride. Remaining solids are usually chlorides of magnesium, sodium, or potassium, or combinations thereof. Thus, the chloride content, assuming the material is 100 percent calcium chloride, introduces very little error.

act primarily by accelerating the hydration of tricalcium silicate (Ramachandran and Malhotra 1984). Calcium chloride should meet the requirements of ASTM D98. Forms of calcium chloride and their equivalent masses are shown in Table 7.2.1.

7.2.2 Soluble organic compounds—The most common organic accelerating admixtures in this class are triethanolamine and calcium formate, which are commonly used to offset the retarding effects of water-reducing admixtures or to provide noncorrosive acceleration. The effectiveness of calcium formate depends on the tricalcium aluminate-to-sulfur trioxide ratio (C_3A/SO_3) of the cement (Gebler 1983). Cements that are under-sulfated (C_3A/SO_3 greater than 4.0) provide the best potential for calcium formate to accelerate the early-age strength of concrete. The production of ettringite is greater in mixtures containing calcium formate (Bensted 1978).

Accelerating properties have been reported for calcium salts of carboxylic acid, including acetate (Washa and Withey 1953), propionate (Arber and Vivian 1961), and butyrate (RILEM 1968a,b). Salts of the higher homologs, however, are retarders (RILEM 1968a,b).

Studies (Ramachandran 1973, 1976a) indicate that triethanolamine accelerates the hydration of tricalcium aluminate but retards hydration of tricalcium silicate. Triethanolamine, therefore, can act as a retarder of cement at high dosages or low temperatures. A number of other organic compounds have been found to accelerate the setting of portland cement when a low w/cm is used. Organic compounds reported as accelerating admixtures include urea (RILEM 1968a,b), oxalic acid (Bash and Rakimbaev 1969; Djabarov 1970), lactic acid (Bash and Rakimbaev 1969; Lieber and Richartz 1972), various cyclic compounds (Lieber and Richartz 1972; Wilson 1927), and condensation compounds of amines and formaldehyde (Roskopf et al. 1975; Kossivas 1971). Retardation can occur if high dosages are used because, like triethanolamine, such compounds will retard the hydration of tricalcium silicate.

7.2.3 Quick-setting admixtures—Quick-setting admixtures are used to produce quick-setting mortar or concrete suitable for shotcreting (16.8.3) and sealing leaks against hydrostatic pressure. These admixtures are believed to act by promoting the flash setting of tricalcium aluminate (Schutz 1977). Ferric salts, sodium fluoride, aluminum chloride, sodium aluminate, and potassium carbonate are reported to produce quick-setting mortars (Mahar et al. 1975), but

many proprietary formulations are mixtures of accelerating admixtures.

Quick-setting admixtures for shotcrete, employed extensively in both the dry and wet processes (ACI 506R), are a specific class of quick-setting admixtures. More information on these products and guidance on their use is found in Chapter 16.

7.2.4 Miscellaneous accelerating materials—In certain instances, hydraulic cements have been used in place of accelerating admixtures. For example, calcium-aluminate cement can cause flash setting of portland-cement concrete (Robson 1952) depending on the dosage rate. Various silicates have been found to act as accelerating admixtures (Angstadt and Hurley 1967; Kroone 1968). Finely divided silica gels and soluble quaternary ammonium silicates have been found to accelerate strength development (Stein and Stevels 1964; Nelson and Young 1977; Wu and Young 1984) through the acceleration of tricalcium silicate hydration. Silica fume (ACI 234R) also accelerates tricalcium silicate hydration (Kurdowski and Nocum-Wezelik 1983; Lu et al. 1993). Adding finely divided magnesium carbonate (Ulfstedt et al. 1961) or calcium carbonate (RILEM 1968a,b) decreases setting times. It is well known that very fine materials of various composition exhibit accelerating properties by acting as nucleation sites for the growth of cement hydration products away from the cement grain surfaces. Recently, additives have been commercialized comprising aqueous solutions of nanoscale nucleation seeds based on calcium-silicate hydrate (C-S-H) phases that provide dramatic early strength acceleration (Thomas et al. 2009; Ditter et al. 2013).

7.3—Selection and evaluation

The selection of an accelerator should be based on its performance with local cements, blended cements, and mixtures containing supplementary cementitious materials (SCMs). Optimum dosage will also vary with the jobsite temperatures. Historical test data can be used to guide the accelerator selection. The effects on a specific mixture design should be determined by individual tests simulating the expected usage conditions. Accelerators will vary in relative performance based on different cement characteristics and concrete temperatures. Nonchloride accelerators are cement-sensitive and produce significantly different results for setting time as well as early strength gain with different cements. The overall effect of their usage with mixtures

containing pozzolans or slag is generally proportional to the amount of cement in the mixture.

Nonchloride accelerators are increasingly being used because of corrosion concerns of engineers and users. Caution is urged with the use of accelerating admixtures in concrete containing shrinkage-compensating cements or shrinkage-compensating components (ACI 223R). Such concretes require evaluation on a case-by-case basis, as the accelerator can affect the timing and the amount of expansion.

Calcium chloride should not be used with calcium aluminate cement because it often retards the hydration of the aluminates. Similarly, both calcium chloride and potassium carbonate retard the setting time and decrease the early strength development of rapid-hardening cements based on calcium fluoroaluminate ($C_{11}A_7-CaF_2$). Strengths at 1 day, however, are improved by these admixtures.

Evaluation of the accelerator requires the comparison of decreased setting time, increased early strength, and the cost of the accelerator versus the nonaccelerated mixture design performance for finishing time, stripping time, and hardened concrete properties. For example, extended retardation of floor and slab concrete allows excessive bleeding, segregation, and early cracking, thereby reducing surface quality. In addition, labor costs are increased because of the extended finishing time or form removal delays. Quality and cost considerations, therefore, can favor the use of accelerating admixtures. Alternate choices in cold weather include the use of high-early-strength cement instead of Type I cement.

Users are also cautioned that some accelerators contain salts of sodium or potassium. When used in high doses, these alkali salts can contribute to alkali-silica reactivity problems if the aggregates used are reactive, making it imperative that the alkali content of accelerators is understood and factored into the available alkali calculations.

7.4—Applications

7.4.1 Reduce placing and finishing time—Accelerating admixtures are commonly used in concrete slabs placed at air temperatures below 50°F (10°C). They will often be used in formed concrete placed at air temperatures below 40°F (4°C). Accelerating admixtures are often used to reduce or normalize the initial set of floors and slabs to reduce the overall placing and finishing time and prevent the ill effects of extended retardation on the quality of the final product.

7.4.2 Increase early strength gain—Accelerating admixtures are regularly used, in a properly proportioned mixture, to achieve early strength gain required by the project specification or the contractor's schedule.

7.4.3 Rapid cycle elevated slab construction—Accelerators are frequently chosen for this type of construction to reduce initial set and provide high early strength. Initial set reduction is required because the contractor will be walking on the slab in the late morning or early afternoon to lay out and form vertical members for the upper floor. High early strength levels should be achieved to allow early stripping and reuse of forms.

7.5—Dosage and proportioning concrete

7.5.1 Fresh concrete properties—Accelerating admixtures change the properties of fresh concrete. Mixture designs should be proportioned in accordance with ACI 211.1, ACI 211.2, or other method. The accelerator dosage will be determined by the desired initial setting time and early strength gain. Water-reducing and accelerating admixtures reduce the water content more than 5 percent. This dosage will be influenced by the setting characteristics of the cement chosen, the member mass, and climatic conditions of temperature and wind. Accelerating admixtures Type C or Type E generally replace the Type A admixture used in a normal-setting mixture. They are added to mixture designs containing high-range water-reducing admixture (HRWRA). In this case, the benefits of the HRWRA for water content, slump level, and w/cm should be maintained. The accelerating admixture dosage is selected to normalize setting time and early strength gain; to significantly increase early strength levels; or, as outlined in Chapter 19, allow concrete operations to take place during cold weather conditions that normally preclude concrete placement.

7.5.2 Initial mixture design—The initial mixture design testing is normally done in a laboratory. The final mixture design selection is based on successful on-site placement to verify setting time; early strength gain; and the standard mixture design qualities such as satisfactory workability, pumpability, or, for slabs, finishing characteristics.

7.5.3 Dosages—Accelerating mixture designs are often prepared with varying dosages. This allows the contractors to base their daily mixture design selections on the actual temperatures and wind conditions, as well as the setting characteristics of the concrete being supplied that day. Often, the mixture design on rapid-cycle projects has a higher dosage of accelerator in the first half of the slab, as that area should set so that the contractor can walk on it in the late morning or early afternoon without marring the surface. In other projects, the accelerator dosage is increased in the last portion of slab concrete to minimize finishing over time.

7.6—Effects on fresh and hardening concrete

7.6.1 Time of setting—Initial and final setting times are reduced by an amount dependent on the dosage of accelerator used, the temperature of the concrete, ambient temperature, and characteristics of other materials used in the concrete. Many accelerators have a greater accelerating effect at 32 to 41°F (0 to 5°C) than at 77°F (25°C). High dosages of accelerating admixtures can cause very rapid setting in hot weather. Excessive dosage rates of certain organic compounds may result in extended times of setting. Similarly, at high dosages (6 percent by mass of cement), calcium nitrate begins to show retarding properties (Murakami and Tanaka 1969), whereas ferric chloride retards at additions of 2 to 3 percent by mass, but accelerates at 5 percent (Roskopf et al. 1975). With quick-setting admixtures, setting times as short as 15 to 30 seconds can be attained. Prepackaged mortar formulations are available that have an initial time of setting of 1 to 4 minutes and a final setting time of 10 to 15 minutes. They are used to seal leaks in below-grade structures for

patching, and for emergency repair. The ultimate strength of such mortar is much lower than if the accelerating admixture had not been added.

7.6.2 Air entrainment—When an accelerating admixture is used, different dosages of air-entraining admixture may be required to produce the required air content. In some cases, however, larger bubble sizes and higher spacing factors are obtained, possibly reducing the beneficial effects of entrained air. Concrete containing a specific admixture may be evaluated to ascertain air-void parameters using **ASTM C457/C457M** or resistance to freezing and thawing using **ASTM C666/C666M**.

7.6.3 Freezing and thawing—Concrete should achieve a compressive strength of 500 psi (3.4 MPa) before freezing. Concrete exposed to freezing and thawing in service should achieve a compressive strength of 4000 psi (27.6 MPa) prior to being exposed to freezing-and-thawing cycles. Properly proportioned mixture designs with accelerators can achieve this strength more quickly.

7.7—Effects on hardened concrete

7.7.1 Discoloration of flatwork—Discoloration of concrete flatwork has been associated with the use of calcium chloride (**Greening and Landgren 1966**). Two major types of mottling discoloration can result from the interaction between cement alkalis and calcium chloride. The first type has light spots on a dark background and is characteristic of mixtures in which the ratio of cement alkalis to calcium chloride is relatively low. The second consists of dark spots on a light background, and is characteristic of mixtures in which the ratio of cement alkalis to chlorides is relatively high. The magnitude and permanence of discoloration increase as the calcium chloride concentration increases from 0 to 2 percent by mass of cement. Discoloration can be aggravated by high rates of evaporation during curing and by improper placement of vapor barriers, which is caused by using sheet membrane for curing that is not kept flat on the surface. Using a continuous fog spray during placement or a proper curing compound can help alleviate this problem.

7.7.2 Strength development—Many accelerators increase compressive strength substantially at early ages. In some cases, later strength may be reduced slightly. Strength gains up to 200 percent/day can be achieved with varying dosages of many accelerators. These early strength levels are dependent on the strength potential of the selected cement. Flexural strength of 400 psi (2.76 MPa) has been achieved in 4 hours with certain accelerators, cements, and high-range water-reducing admixtures (HRWRAs). Certain accelerators with HRWRAs have easily achieved 4000 psi (27.6 MPa) in 12 hours in the laboratory and in the field. The percentage increase in flexural strength is usually less than that of the compressive strength (**Ramachandran 1976b**). The effects of other accelerating admixtures on strength development are not completely known, although other calcium salts behave similarly. Because accelerated strength development depends on accelerated hydration, heat of hydration also develops faster, but there is no appreciable effect on total heat generation. Quick-setting admixtures, such as

carbonates, silicates, and aluminates, may decrease concrete strengths and ultimate strengths as early as 1 day (**Mailvaganam 1984**). Quick-setting mixtures of portland cement and calcium-aluminate cement behave similarly. Organic compounds such as triethanolamine and calcium formate appear to be sensitive in their accelerating action to the particular concrete mixture to which they are added, and to the ambient temperature.

Preliminary laboratory tests should be followed by field tests to assure that the proposed mixture design easily achieves the target strength levels at early and late ages without presenting placing or finishing problems due to too-quick setting characteristics.

7.7.3 Volume change—Accelerating admixtures can increase the volume changes that occur under moist curing and drying conditions. Calcium chloride can increase creep and drying shrinkage of concrete (**Shideler 1942**). **Mather (1964)** offered an alternative hypothesis to the presumed association of the use of calcium chloride with increased drying shrinkage. **Bruere et al. (1971)** observed that such volume changes depend on the length of curing before beginning measurements, the length of the drying or loading periods, and composition of the cement used. They also noted that changes in the rate of deformation are greater than changes in the total deformation. **Berger et al. (1967)** suggested that the influence of calcium chloride in drying shrinkage can result from changes in the size distribution of capillary pores due to calcium chloride's effect on hydration of the cement. Drying shrinkage and swelling in water are higher for mixtures containing both portland calcium-aluminate cements and calcium chloride, and their durability may be adversely affected by using an accelerating admixture (**Feret and Venuat 1957**). Excessive shrinkage and subsequent cracking can significantly decrease durability characteristics. Therefore, shrinkage tests on the proposed mixtures should be required.

7.7.4 Freezing and thawing—Properly proportioned mixtures with the proper air content and w/cm and many accelerators provide very satisfactory long-term resistance to freezing and thawing.

7.7.5 Chemical attack—Resistance to sulfate attack is decreased when conventional portland-cement concrete mixtures contain calcium chloride (**U.S. Bureau of Reclamation 1975**), but when used with Type V cement to mitigate the effects of cold weather, it is not harmful (**Mather 1992**). The expansion produced by alkali-silica reaction (ASR) is greater when calcium chloride is used (U.S. Bureau of Reclamation 1975). Nonchloride admixtures may increase expansion.

7.8—Corrosion of metals

One of the major disadvantages of calcium chloride is that it induces corrosion of metals embedded in concrete when in the presence of sufficient moisture and oxygen. **ACI 318** lists the chloride limits for concrete in new construction that should be used to determine the maximum permissible water-soluble chloride-ion content for concrete in various types of construction (Table 7.8a). Table 7.8b shows the maximum and water-soluble chloride limits for new construction