Report on Chemical Admixtures for Concrete

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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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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 manufacture.
Table 1.2—Admixtures, their characteristics, and usage

<table>
<thead>
<tr>
<th>Admixture type (Chapter number)</th>
<th>Effects and benefits</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>(6) Mid-range water-reducing (ASTM C494/C494M, Type A)</td>
<td>Reduce water content by between 5 and 10 percent without retardation of initial set.</td>
<td>Lignosulfonic acids and their salts. Polycarboxylates.</td>
</tr>
<tr>
<td>(6) High-range water-reducing (ASTM C494/C494M; AASHTO M 194/M 194, Type F or G)</td>
<td>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).</td>
<td>Melamine sulfonate polycrystalline products, naphthalene sulfonate polycrystalline products, and polycarboxylates.</td>
</tr>
<tr>
<td>(7) Accelerating (ASTM C494/C494M; AASHTO M 194/M 194, Type C or E)</td>
<td>Accelerate setting and early strength development.</td>
<td>Calcium chloride (ASTM D98; AASHTO M 144), triethanolamine, sodium thiocyanate, sodium/calcium formate, sodium/calcium nitrite, calcium nitrate, aluminates, and silicates.</td>
</tr>
<tr>
<td>(8) Set-retarding (ASTM C494/C494M and AASHTO M 194/M 194, Type D)</td>
<td>Reduce water content at least 5 percent. Delay set time.</td>
<td>Refer to water-reducing materials.</td>
</tr>
<tr>
<td>(9) Extended set-controlling (hydration control) (ASTM C494/C494M, Type B or D)</td>
<td>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. Return slump life in a more consistent manner than normal retarding admixtures.</td>
<td>Carboxylic acids. Phosphorus-containing organic acid salts.</td>
</tr>
<tr>
<td>(10) Workability retaining</td>
<td>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</td>
<td>Dispersants such as polycarboxylates.</td>
</tr>
<tr>
<td>(11) Viscosity- and rheology-modifying</td>
<td>Modify the rheological properties of plastic concrete.</td>
<td>Polyethylene oxides, cellulose ethers (HEC and HPMC), alginites (from seaweed), natural and synthetic gums, and polyacrylamides or polyvinyl alcohol.</td>
</tr>
<tr>
<td>(12) Shrinkage-reducing and shrinkage-compensating</td>
<td>Reduce drying shrinkage. Reductions of 30 to 50 percent can be achieved.</td>
<td>Polyoxyalkylene alkyl ether, propylene glycol, calcium sulfosalts, calcium-aluminate, calcium-hydroxide- or magnesium oxide-based systems.</td>
</tr>
<tr>
<td>(14) Lithium admixtures to reduce deleterious expansions from alkali-silica reaction</td>
<td>Minimize deleterious expansions from alkali-silica reaction.</td>
<td>Lithium nitrate, lithium carbonate, lithium hydroxide, and lithium nitrite.</td>
</tr>
<tr>
<td>(15a) Permeability-reducing admixture: non-hydrostatic conditions (PRAN)</td>
<td>Water-repellent surface, reduced water absorption.</td>
<td>Long-chain fatty acid derivatives (stearic, oleic, caprylic capric), soaps and oils (tallow, soya-based), petroleum derivatives (mineral oil, paraffin, bitumen emulsions), and fine particle fillers (silicates, bentonite, talc).</td>
</tr>
<tr>
<td>(15b) Permeability-reducing admixture: hydrostatic conditions (PRAH)</td>
<td>Reduced permeability, increased resistance to water penetration under pressure.</td>
<td>Crystalline hydrophilic polymers (latex, water-soluble, or liquid polymer).</td>
</tr>
<tr>
<td>(16a) Bonding</td>
<td>Increase bond strength.</td>
<td>Polyvinyl chloride, polyvinyl acetate, acrylics, and butadiene-styrene copolymers.</td>
</tr>
<tr>
<td>(16b) Coloring</td>
<td>Colored concrete.</td>
<td>Carbon black, iron oxide, phthalocyanine, raw burned umber, chromium oxide, and titanium dioxide.</td>
</tr>
<tr>
<td>(16c) Flocculating</td>
<td>Increase interparticle attraction to allow paste to behave as one large flock.</td>
<td>Vinyl acetate-maleic anhydride copolymer.</td>
</tr>
<tr>
<td>(16d) Fungicidal, cemicidal, insecticidal</td>
<td>Inhibit or control bacterial, fungal, and insecticidal growth.</td>
<td>Polyhalogenated phenols, emulsion, and copper compounds.</td>
</tr>
<tr>
<td>(16f) Expansive/gas forming</td>
<td>Control settlement and bleeding and improve the intrusion of grout and mortars.</td>
<td>Metallic aluminum, zinc or magnesium, hydrogen peroxide, nitrogen and ammonium compounds, and certain forms of activated carbon or fluidized coke.</td>
</tr>
<tr>
<td>(16g) Cellular</td>
<td>Air-generating admixtures for the production of flowable fill, lightweight concrete, insulation.</td>
<td>Protein and other synthetic surfactants.</td>
</tr>
<tr>
<td>(16h) Shotcrete</td>
<td>Shotcrete accelerators for wet and dry mixture applications.</td>
<td>Alkali-based and alkali-free materials.</td>
</tr>
<tr>
<td>(16i) MCP</td>
<td>Production efficiency, surface texture and strength.</td>
<td>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 coal waxes.</td>
</tr>
</tbody>
</table>
CHAPTER 2—DEFINEDS

2.1—Definitions


**alkali-silica reaction**—generally deleterious dissolution and swelling of siliceous aggregates in the presence of pore solutions comprised of alkali hyroxides; 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.

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 characteristicsf) Reduce segregation
g) Improve finishability
h) Improve pumpability
i) Modify rheological properties
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:

b) Water-reducing and set-controlling admixtures: ASTM C494/C494M and AASHTO M 194/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 around a
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, forming, placing, and joining separate units. Accelerating admixtures reduce finishing and placing 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 Aitcin 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 AS1M 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 as outlined by the purchaser, project specification, or both. The admix-
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 admixtures 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 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)
da) 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 though 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)
         iii. Reducing emissions and energy consumption through faster concrete truck discharge rates and faster concrete placements (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)
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### Constructibility attributes required

| Workability | Flowability | Finishability | Self-consolidating | Cohesive | Fast-setting | Slow-setting | High early strength | Bleeding control | Hot weather | Cold weather | Sub-freezing weather | Underwater | Pumped | Long haul/long placement | Long pump distance | Fast-track construction | Congested reinforcing bar | Difficult access to consolidate | Extruded concrete | High strength | High modulus of elasticity | Low shrinkage | Low curling | Reduced cracking | Reduced creep | Damp-proof/low absorption | Low permeability | Extended joint spacings | Lightweight/cellular | Damp-proof/low absorption | Low permeability | Extended joint spacings | Lightweight/cellular |
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### Special construction conditions

| Concrete requirements exposures | Hot weather | Cold weather | Sub-freezing weather | Underwater | Pumped | Long haul/long placement | Long pump distance | Fast-track construction | Congested reinforcing bar | Difficult access to consolidate | Extruded concrete | High strength | High modulus of elasticity | Low shrinkage | Low curling | Reduced cracking | Reduced creep | Damp-proof/low absorption | Low permeability | Extended joint spacings | Lightweight/cellular | Damp-proof/low absorption | Low permeability | Extended joint spacings | Lightweight/cellular |
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### Special engineering properties/applications

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### Special environment conditions in service

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### Special aesthetic considerations

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### Special concrete/structure/element considerations

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### Refer to cautions for air in steel trowel floor.

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*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, drive-ways, 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 μm to 1.18 mm) (No. 16 to 50 sieve
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6HUHGD may have the ability to provide a stable void system. Once materials that provide resistance to cyclic freezing and thawing (during the expansion of freezing water within concrete similar to entrained air voids, providing stress relief zones in laboratory tests using produced concrete with resistance to freezing and thawing. Inclusion of such particulates in the proper proportion has 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-

<table>
<thead>
<tr>
<th>Admixture type</th>
<th>Effect on concrete</th>
<th>Sustainability impact—concrete production</th>
<th>Sustainability impact—initial construction</th>
<th>Sustainability impact—life cycle</th>
</tr>
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<tbody>
<tr>
<td>Extended set-control admixtures</td>
<td>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.</td>
<td>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.</td>
<td>Allows full load delivery in slow placement situations where normally short loads would be needed; eliminating second truck cycle environmental footprint.</td>
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<tr>
<td>Water-reducing and mid-range water-reducing</td>
<td>Less water, resulting in less cement for equivalent strength.</td>
<td>Less water consumed per volume of concrete.</td>
<td>Lower carbon footprint through reduction in cementitious materials.</td>
<td>—</td>
</tr>
<tr>
<td>High-range water-reducing</td>
<td>Less water, resulting in less cement for equivalent strength. Higher slump at equal water.</td>
<td>Less water consumed per volume of concrete.</td>
<td>Substantially lower carbon footprint through reduction in cementitious materials. Reduction in construction labor, reducing related carbon footprint.</td>
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<tr>
<td>Accelerating admixtures</td>
<td>Accelerate hydration, especially in cold weather.</td>
<td>Reduce or eliminate need for hot water or heated aggregates.</td>
<td>Reduce heating forms and reduce heated enclosures.</td>
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<tr>
<td>Admixtures for self-consolidating concrete</td>
<td>Much higher workability at equal water.</td>
<td>Faster truck discharge and placement rates.</td>
<td>Markedly reduced placement labor and related carbon footprint.</td>
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<tr>
<td>Air-entraining admixtures</td>
<td>Low cement content mixtures; air replaces water volume, giving water reduction. Stable air void distribution, lower permeability.</td>
<td>Some types promote early strength, reducing elevated curing requirements.</td>
<td>—</td>
<td>Lower carbon footprint through reduction in cementitious materials and in some cases sand. More durable concrete-enhancing service life.</td>
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<tr>
<td>Corrosion-inhibiting admixtures</td>
<td>Delays onset of reinforcing steel corrosion in salt environments.</td>
<td>Some types promote early strength, reducing elevated curing requirements.</td>
<td>Eliminates the carbon footprint of epoxy-coated reinforcing.</td>
<td>Extends service life.</td>
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<tr>
<td>Permeability-reducing admixtures</td>
<td>Decreased permeability, longer time to corrosion.</td>
<td>—</td>
<td>Eliminates need for post-placement applied barrier, compressing the construction schedule and associated carbon footprint.</td>
<td>Extends service life.</td>
</tr>
<tr>
<td>Shrinkage-reducing admixtures</td>
<td>Reduces cracking due to shrinkage; can allow longer joint spacing in some instances.</td>
<td>—</td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>Admixtures for coloring concrete</td>
<td>Lighter-colored concrete.</td>
<td>—</td>
<td>—</td>
<td>Lower heat island effect in paved areas. Reduction in lighting load, for example, in parking garages.</td>
</tr>
<tr>
<td>Admixtures for pervious concrete</td>
<td>Facilitates placement, speed truck discharge, and improves raveling resistance.</td>
<td>More complete truck discharge reduces returned concrete.</td>
<td>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.</td>
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Table 4.2—Admixture types and their environmental impact
ure 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/m.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 (Tyness 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 μm] 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 shotcrete 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 (Segrebrecht 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 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 required to produce a given air content 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 increased from approximately
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—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 MRWRAs, 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). HRWRAs 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. MRWRAs 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 polycodensation products
5) Salts of sulfonated naphthlene polycodensation 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 construction 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 less effective than a single dose (Carraquillo and Carraquillo
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 reproportioned 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 C3A, C3S, 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 SO3 content in the cement may be desirable when using HRWRAs because the SO3 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 and set-retarding 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, \(w/c\) ratio, 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 \(w/c\) 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 \(w/c\), 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 \(w/c\), the 28-day compressive strength can increase by 25 percent or more. Because of their effectiveness in reducing \(w/c\), 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 \(w/c\), 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 \(w/c\). When used to reduce the \(w/c\), 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 nitrates, either separately or combined.

7.2.1 Soluble inorganic salts—Studies (Edwards and Angstadt 1966; Rosskopf et al. 1975) have shown that a variety of soluble inorganic salts, including chlorides, bromides, fluorides, carbonates, thiocyanates, nitrates, 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 numerous investigators has shown that inorganic accelerating admixtures
Table 7.2.1—Calcium chloride: amount introduced

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

*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 (C₃A/SO₃) of the cement (Gebler 1983). Cements that are under-sulfated (C₃A/SO₃ 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 Withay 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 products 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 (Kurkowski 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...
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 (Rosskopf 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 3 to 10 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 alakals and calcium chloride. The first type has light spots on a dark background and is characteristic of mixtures in which the ratio of cement alkals 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 alkals 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 (Mallvaganam 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 watersoluble chloride-ion content for concrete in various types of construction (Table 7.8a). Table 7.8b shows the acid-soluble and water-soluble chloride limits for new construction.
reported by ACI 222R. Gaynor (1985) discusses the calculation of chloride contents for comparison with these limits, as seen in Table 7.8c. The user should evaluate the chloride levels from all ingredients. Other factors such as moisture and oxygen are always necessary for electrochemical corrosion. Many nonchloride-based accelerators are available. The use of calcium chloride will aggravate the effects of poor-quality concrete construction, particularly when the concrete is exposed to chlorides during service. When good concrete practices are followed, the limits listed in Table 7.8a have shown to be highly effective in limiting corrosion. The user should determine whether a nonchloride accelerator would be a better choice in the particular type of construction. The chlorides contributed by all ingredients should then be determined. The potential for in-service corrosion should be evaluated accordingly.

Background chloride contents in concrete are naturally-occurring chlorides in the concrete materials. When background chloride or when the chloride content is found to be excessive, the Soxhlet Method should be conducted for final acceptance. The Soxhlet Method for aggregates is detailed in ASTM C1524.

If the concrete or mortar fails the acid-soluble test according to ASTM C1152/C1152M, then the water-soluble test must be conducted according to ASTM C1218/C1218M. If the results from the water-soluble test fail, then the Soxhlet method for water-soluble (extractable) chloride may be conducted.

Admixtures based on calcium nitrate or thiocyanates have been proven effective in accelerating initial set and early strength gain. The fact that an accelerating admixture does not contain significant amounts of chloride, however, does not necessarily render it noncorrosive. For example, Manns and Eichler (1982) report that thiocyanates may promote corrosion. Nmai and Corbo (1989), however, found that the threshold level for initiation of corrosion by soda thoriumate lies between 0.75 and 1.0 percent by mass of cement, and concluded that the use of sodium thoriumate-based accelerating admixtures is safe for reinforced concrete applications up to these concentrations. Typical dosages of accelerating admixtures containing sodium thiocyanate contribute between 0.05 and 0.1 percent sodium thiocyanate by mass of cement, and extremely high dosages may contribute as much as 0.2 percent sodium thiocyanate. Users may request that suppliers of all nonchloride admixtures provide information regarding the corrosion of steel in concrete. The information should include corrosion results within the intended dosage range.

### Table 7.8a—Maximum chloride-ion concentration for corrosion protection (ACI 318-14)

<table>
<thead>
<tr>
<th>Type of member</th>
<th>Maximum water-soluble chloride ion in concrete, percent by weight of cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prestressed concrete</td>
<td>0.06</td>
</tr>
<tr>
<td>C0: Concrete dry or protected from moisture</td>
<td>1.00</td>
</tr>
<tr>
<td>C1: Concrete exposed to moisture but not to an external source of chloride</td>
<td>0.30</td>
</tr>
<tr>
<td>C2: Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### Table 7.8b—Chloride limits for new construction (ACI 222R)

<table>
<thead>
<tr>
<th>Category</th>
<th>Chloride limit for new construction, percent by mass of cement</th>
<th>Test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid-soluble</td>
<td>Water-soluble</td>
<td></td>
</tr>
<tr>
<td>Prestressed concrete</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>Reinforced concrete in wet conditions</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Reinforced concrete in dry conditions</td>
<td>0.20</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### Table 7.8c—Calculation of total chloride-ion content*

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>lb/yd³ (or dosage)</th>
<th>Total Cl⁻, percent by weight of each material</th>
<th>Calculation</th>
<th>Total Cl⁻, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>600</td>
<td>0.005</td>
<td>(0.005)(600) (10⁻²)</td>
<td>0.03</td>
</tr>
<tr>
<td>Sand (SSD)</td>
<td>1150</td>
<td>0.01</td>
<td>(0.01)(1150) (10⁻²)</td>
<td>0.115</td>
</tr>
<tr>
<td>Coarse aggregate (SSD)</td>
<td>1800</td>
<td>0.106</td>
<td>(0.106)(1800) (10⁻²)</td>
<td>1.908</td>
</tr>
<tr>
<td>Water</td>
<td>280</td>
<td>0.250 ppm</td>
<td>(280)(0.250) (10⁻⁴)</td>
<td>0.07</td>
</tr>
<tr>
<td>Admixture</td>
<td>(5 oz/100 lb)</td>
<td>800 ppm</td>
<td>(800)(5)(1/16)(10⁻⁴)</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

*Per 100 lb of cement.

Notes: Total Cl⁻ in yd³ = 2.1245 lb; total chloride, percent by weight of cement = [(2.1245/600)(0.250) = 0.354 percent; 1 lb/yd³ = 0.5933 kg/m³; 1 lb = 0.4536 kg; 1 yd³ = 0.7646 m³; and 1 oz = 29.574 mL.

Accelerator performance in properly designed mixtures should be monitored regularly by checking concrete temperatures, initial set, and the early strength levels expected. A correlation should be developed between laboratory-cured compressive strength cylinders versus in-place concrete strengths determined from cores, and monitored in accordance with the maturity method. Cylinders are often cured in the field to verify the predicted early strength levels are being achieved. Cylinders tested in this manner have a much higher specific surface than the member and are much more rapidly and substantially affected by ambient temperature as a result. The maturity method, based on thermocouple probes inserted into the slab, has proven accurate in predicting early strengths based on temperature developments of the pretested mixture design.

### 7.9—Quality assurance and batching

Accelerator performance in properly designed mixtures should be monitored regularly by checking concrete temperatures, initial set, and the early strength levels expected. A correlation should be developed between laboratory-cured compressive strength cylinders versus in-place concrete strengths determined from cores, and monitored in accordance with the maturity method. Cylinders are often cured in the field to verify the predicted early strength levels are being achieved. Cylinders tested in this manner have a much higher specific surface than the member and are much more rapidly and substantially affected by ambient temperature as a result. The maturity method, based on thermocouple probes inserted into the slab, has proven accurate in predicting early strengths based on temperature developments of the pretested mixture design.
7.9.1 Strength development—The strength level of the actual concrete member is particularly important so that the project schedule can be met without risk to the concrete team. Cold weather concreting operations present a challenge to the concrete contractor and concrete producer. The number and type of tests used to assure strength level attainment should be thoroughly discussed at the preconcrete conference and implemented carefully in the field.

7.9.2 Field testing—Valuable field testing also involves monitoring the temperature of the concrete upon arrival and later in the slab. Because the concrete temperature directly affects the hydration process, it is an accurate predictor of concrete performance that day. Concrete that loses 5°F (3°C) or more in the first hour after placement indicates that the mixture design contains slow-setting cement, excessive amounts of supplementary cementitious materials, a too-low dosage or the wrong choice of an accelerator, or all of these factors. An increase in dosage could solve the problem. The measures advocated in ACI 306R should be implemented in all cases.

7.9.3 Batching—Accelerating admixtures should be added to the mixture in solution form. Nonchloride accelerators are generally added at a dosage range of 10 to 30 ft oz/100 lb (652 to 1956 mL/100 kg) of cementitious material. Calcium chloride solutions, where permitted, are generally added at 1 to 2 percent lb of solids/100 lb of cement (kg/mass of cement). The typical calcium chloride-based accelerator solids content is 30 percent or approximately 10.6 lb/gal. (1.3 kg/L). The nonchloride accelerators range in solids content from 40 to 60 percent. The correct density should be obtained from the supplier.

CHAPTER 8—SET-RETARDING ADMIXTURES

8.1—Introduction
Water-reducing set-retarding admixtures reduce the water requirements of a concrete mixture for a given slump and increase the time of setting. Set-retarding admixtures increase the set time of concrete without affecting the water requirements. Chapter 6 addresses normal-setting water-reducing admixtures. Water-reducing set-retarding admixtures and set-retarding admixtures should meet the requirements of ASTM C494/C494M Types B and D, respectively. Set-retarding high-range water-reducing admixtures (HRWRAs) should meet the requirements of ASTM C494/C494M Type G. The change in time of setting depends on the relative amounts of each ingredient used in the formulation.

Although a few materials are available that exert only a retarding influence on concrete with little or no water-reducing capacity, the vast majority of admixtures referred to as retarders are actually water-reducing set-retarding admixtures (Mailvaganam and Rixon 2002).

Chapter 9 addresses extended set-control admixtures (ESCA), commonly referred to as hydration-controlling admixtures (HCAs), which are used to stop or severely retard the cement hydration process in unhardened concrete for use in returned/waste concrete, wash water, or very long hauls.

8.2—Materials
8.2.1 Classification—Water-reducing set-retarding admixtures and set-retarding admixtures should meet the applicable requirements of ASTM C494/C494M, which defines three types of set-retarding admixtures:
1) Type B—Retarding admixtures
2) Type D—Water-reducing and retarding admixtures
3) Type G—Water-reducing, high-range, and retarding admixtures

ASTM C494/C494M gives detailed requirements for water requirements, setting time, flexural and compressive strength, drying shrinkage, and resistance to freezing and thawing. The specific effects of water-reducing set-retarding admixtures and set-retarding admixtures, however, vary with different cements, addition sequences, changes in w/cm, mixing temperature, ambient temperature, and other site conditions. Most water-reducing set-retarding admixtures and set-retarding admixtures perform considerably better than the minimum requirements of ASTM C494/C494M in regards to water reduction and compressive strength. The dosage at which a water-reducing admixture meets the performance requirements in ASTM C494/C494M with a given cement can be higher or lower when tested with different concrete ingredients and proportions.

8.2.2 Compositions—Materials generally available for use as water-reducing set-retarding admixtures and set-retarding admixtures fall into one of four 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) Inorganic salts such as borates and phosphates

8.3—Selection and evaluation
If adequate information is unavailable, tests should be done to evaluate the effect of the water-reducing set-retarding admixtures and set-retarding admixtures on the properties of concrete made with job materials under the anticipated ambient conditions and construction procedures. Tests of water-reducing set-retarding admixtures should indicate their effect on the following properties of concrete, insofar as they are pertinent to the project:

a) Water requirement
b) Air content
c) Slump
d) Bleeding
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 set-retarding admixtures and set-retarding admixtures are evaluated in laboratory trial
8.7—Effects on fresh and hardening concrete

8.7.1 Water reduction—Water-reducing set-retarding admixtures decrease the water required for the same slump concrete by at least 5 percent. Concrete containing lignosulfonate or hydroxylated carboxylic acid salts can reduce the water content 5 to 10 percent for a given slump and cement content. Retarding high-range water-reducing admixtures (HRWRAs) provide at least 12 percent water reduction.

8.7.2 Air entrainment—Some water-reducing set-retarding admixtures and set-retarding 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; Rixom and Mailvaganam 1999). The air-entraining properties can be controlled by modifying the formulations.

8.7.3 Workability—When comparing a concrete mixture without a water-reducing set-retarding admixture of the same slump and air content, differences in workability are difficult to detect. Rheometers are useful in determining workability, flowability, and viscosity (Ferraris et al. 2000). Concrete containing a water-reducing set-retarding admixture, however, is less likely to segregate and sometimes has better flowability.

8.7.4 Bleeding—Water-reducing set-retarding admixtures affect bleeding capacity in varying degrees. For example, unmodified hydroxylated carboxylic admixtures (8.2.2) tend to increase bleeding. Lignosulfonate admixtures (8.2.2) may reduce bleeding and segregation in freshly mixed concrete, partly due to the air entrainment (Mailvaganam and Rixom 2002). Retarding HRWRAs may decrease bleeding, except at very high slump.

8.7.5 Rate of slump loss—The rate of slump loss may be decreased by adding water-reducing and set-retarding admixtures. Working time can be extended with the careful use of an ASTM C494/C494M Type B retarding or Type D water-reducing and retarding admixture, or with the use of a Type G retarding HRWA. The working time depends on many factors, including the admixture dosage, use of other chemical admixtures, cement characteristics, water to cement ratio, concrete temperature, slump, and age of the concrete.

8.7.6 Finishing—Some water-reducing and set-retarding admixtures improve the concrete’s finishing characteristics compared to concrete containing no admixture.

8.7.7 Time of setting—Water-reducing and set-retarding admixtures cause a delay in setting time that will increase with increasing dosages and lower temperatures (Ramachandran 1995). Set-retarding admixtures are not recommended for controlling false set; some water-reducing and set-retarding admixtures have been reported to contribute to premature stiffening. Lignosulfonate admixtures can delay false set, and sugar-type admixtures can cause flash set if the cement has a low sulfate-to-aluminate ratio.

8.7.8 Heat of hydration—Within normal water to cement ratios, heat of hydration and adiabatic temperature rise are not reduced at equal cement contents with the use of water-reducing admixtures. Set-retarding admixtures 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 is considered necessary, the heat of hydration should be measured under field conditions.

8.4—Applications

Set-retarding admixtures are used primarily to offset the accelerating effect of high ambient temperature (hot weather) and to keep concrete workable during the entire placing period. This method is particularly valuable to prevent cracking of concrete beams, bridge decks, or composite construction caused by form deflections. Set-retarding admixtures are also used to keep concrete workable long enough so that succeeding lifts can be placed without development of cold joints in the structural unit (Rixom and Mailvaganam 1999). Their effects on rate of slump loss vary with the particular combinations of materials used. In hot weather conditions, concrete should be placed in accordance with ACI 305R.

8.5—Dosage

The expected performance of a given brand, class, or type of water-reducing set-retarding admixtures and set-retarding admixtures may 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

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 cement, aggregates, other materials, and weather conditions.

8.6—Proportioning concrete

When a concrete mixture considered satisfactory in workability and finishing qualities is modified to incorporate a water-reducing set-retarding admixture, the ratio of mortar to coarse aggregate by volume should remain the same. Changes in water content, 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 set-retarding admixtures are water solutions. The proportional volume of water contributed by the admixture is so small in relation to the size of the batch that it can usually be neglected.
set-retarding admixtures permits a reduction in cement content, the heat generated is proportionally reduced.

8.7.9 Shrinkage—Retarders may increase plastic shrinkage if the duration of the plastic stage is extended and the concrete is not protected from loss of moisture, but drying shrinkage is not affected (Neville 1995).

8.8—Effects on hardened concrete

8.8.1 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 set-retarding admixture. Used at high dosages, set-retarding admixtures can decrease the strength at ages up to 24 hours whereas the normal-setting and accelerating admixtures increase the very early strength. Later-age strength with a water-reducing set-retarding admixture can increase 20 percent or more at the same cement content. Cement contents can thus be reduced without lowering 28-day strengths. Concrete with slow early strength gain generally exhibits higher later strengths (Rixom and Mailvaganam 1999; ACI 363R).

8.8.2 Resistance to freezing and thawing—Water-reducing set-retarding admixtures and set-retarding 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 critically saturated in the presence of water.

8.9—Quality assurance and batching

Water-reducing set-retarding admixtures and set-retarding admixtures are typically batched and dispensed as liquids. They should be batched following the manufacturer’s recommendations. Storage tanks for admixtures should be clearly identified, and the solutions should be protected from contamination, dilution, evaporation, and freezing.

CHAPTER 9—EXTENDED SET-CONTROL ADMIXTURES

9.1—Introduction

Extended set-control admixtures (ESCA) or hydration-controlling admixtures (HCA) are used to stop or severely retard the cement hydration process in unhardened concrete. The ESCA should be added and thoroughly mixed with the unhardened concrete (either freshly batched or returned) before the concrete approaches its initial setting time. ESCAs differ from conventional set-control admixtures because they stop the hydration process of both the silicate and aluminate phases in portland cement. Regular set-control admixtures act only on the silicate phases.

9.2—Materials

The most effective materials are carboxylic acids and phosphorus-containing organic acids and salts (Kinney 1989; Senbeta and Dolch 1991; Senbeta and Scanlon 1991). Such admixtures have gained increased acceptance since their introduction in 1986.

9.3—Selection and evaluation

These admixtures should be evaluated for their effects on set time under the existing environmental conditions and with actual materials to be used. As they are typically used at high dosages, slight differences in the response seen with normal doses of ordinary retarders as cements or other material change can be amplified. Testing at expected concrete temperatures with actual materials is therefore essential. Proper mixture proportioning is essential for maintaining specified concrete quality in both the plastic and hardened state.

9.4—Applications

The technology of extended set-control admixtures (ESCA) has shown value in two basic application areas for the concrete producer; they are used to:

1) Shut down ongoing hydration of cementitious products in returned/waste concrete or in wash water that has been treated in the truck or in a concrete reclaimer system, which allows these products to be recycled back into concrete production so that they need not be disposed of;

2) Stabilize freshly batched concrete to provide medium- to very long-term set retardation, which allows concrete to remain plastic during very long hauls or in long-distance pumping situations that require long slump life in a more predictable fashion than normal retarders.

9.4.1 Treating concrete wash water in mixer drum—This process eliminates the disposal of water used to wash out the inside of truck mixers while still keeping the blades and inner surface of the drum clean. This process is designed for overnight or weekend stabilization of 40 to 70 gal. (150 to 270 L) of wash water using a low dosage of an ESCA. Following the stabilization period, the water content of freshly batched concrete is reduced to compensate for the stabilized residue held in the truck mixer. Concrete containing stabilized residue shows setting times equal to concrete without stabilized residue, with performance characteristics equal to or better than conventional concrete.

9.4.2 Stabilization of returned unhardened concrete—In this application, returned concrete can receive same-day stabilization for 1 to 4 hours or longer with a low dosage of an ESCA. This application reuses returned unhardened concrete during the same production day instead of disposal, typically without any added accelerator because the ESCA doses are low. Another option is to treat returned unhardened concrete overnight. Depending on the blend ratio of stabilized to fresh concrete, an accelerating admixture (chloride-bearing or nonchloride) may need to be added the next morning to reinitiate hydration. Fresh concrete is batched on top of the stabilized, or stabilized and activated, concrete to complete the normal load. The combination of fresh concrete and stabilized concrete should harden similarly to conventionally batched concrete without an ESCA, provided the manufacturer’s guidelines and testing described in the following are carefully followed. Guidelines on the type of mixtures and time/temperature constraints on mixtures eligible for stabilization should be established by testing, and be adhered to. Be sure to determine the acceptable ratio of stabilized to fresh concrete. This is especially important in
overnight stabilization, as the typical busy nature of the early morning batching tends to make following these guidelines difficult. If too much stabilized concrete is combined with too little fresh concrete, excessive retardation can result. Extensive testing and ongoing monitoring is required for the successful practice of this method to maintain correct doses of ESCA, and accelerator where required, as the result of changing materials and temperature conditions. The purchaser's consent should always be obtained for delivery of loads containing a blend of fresh and stabilized concrete.

9.4.3 Stabilization of cement fines in gray water (concrete slurry water) in reclaimer systems—In this application, ESCAs are used to enhance traditional concrete reclaimer systems by stabilizing the hydration of cement fines in the slurry or gray water. This can reduce maintenance issues with the reclaimer by preventing hydration and improve the resulting concrete by stopping the hydration of the cement in the gray water. Several combinations of these technology and reclaimer systems have been used, but the most successful are modeled after the prevailing practice in Japan as described by Nakamura and Roberts (1998).

In this type of arrangement, a set dose of ESCA is added to a tank of water. This treated water is then used to rinse out returning trucks and recirculated until the suspended solids, which are composed primarily of partially hydrated cement grains, reach a predetermined limit. This gray water of known solids content is transferred into another tank that is then used to make up as much as 100 percent of the batch water used in regular concrete production. ASTM C94/C94M has optional limits on suspended solids in batch water of 5 percent by weight, although recycling systems containing ESCAs have been shown to operate successfully with gray water containing 10 percent or more suspended solids. ASTM C94/C94M allowance of wash water use in ready mixed concrete mandates that set time not vary from reference by more than 1 hour earlier, nor more than 1.5 hours later; and compressive strength at 7 days shall not be less than 90 percent of reference. By using the proper amount of ESCA in this type of system, the incorporation of the gray water is essentially neutral regarding set and slump life while providing modest strength enhancement from the extra unreacted cement content relative to identical concrete batched with potable water.

9.4.4 Stabilization of freshly batched concrete for long hauls—Extended set-control admixtures can be used to stop the hydration process for extended hauls and reduce or eliminate slump loss and concrete temperature increase during transit. For this application, the ESCA is added during or immediately after the initial batching process. Once the admixture is thoroughly mixed into the fresh concrete, the mixer drum should turn as slowly as possible. The ESCA dosage should be adjusted so the setting time of the concrete is extended for the duration of the haul. Ideally, on arrival at the jobsite, the effects of the admixture should be completed. This will allow the stabilized concrete to set similarly to normal concrete at the site. This application is especially helpful in summer months when hydration is accelerated due to elevated ambient and material temperatures.

9.4.5 Pervious concrete—According to Huffman (2005) and Bury et al. (2006), ESCAs are commonly used in pervious concrete to extend the window of placeability and compaction by extending the period of fluidity of the cement paste.

9.5—Dosage and proportioning concrete

Dosages vary widely depending on the type of extended set-control admixtures (ESCA), application type, duration of set stabilization, materials treated, and environmental conditions. For use in freshly batched concrete to extend set times, the doses will vary from as little as 2 fl oz/cwt (1.304 mL/kg) to as much as 48 fl oz/cwt (26.08 mL/kg). To stabilize returned concrete, the dose can vary from 4 fl oz/cwt (2.608 mL/kg) to as much as 128 fl oz/cwt (83.456 mL/kg). To stabilize wash water in a concrete truck, the dose may vary from 4 fl oz (118 mL) to as much as 64 fl oz (1.89 L) per truck (with 10 to 70 gal. [38 to 266 L] of water). For use in reclaimer systems, the dose to treat 1000 gal. (3800 L) of gray water is typically in the range of 0.75 to 2 gal. (2.85 to 10 L) of ESCA, depending on temperature conditions and maximum expected residence time of the gray water. Refer to Nakamura and Roberts (1998) for an explanation of dosing per unit water. For all situations, it is essential to test with actual materials to be used at the prevailing temperature conditions.

9.6—Effects on fresh and hardening concrete

When used to extend set in freshly batched concrete, the dominant effect is merely to increase set time. Once the retarding effect wears off and hydration commences, the concrete will typically exceed the strength of a reference concrete exposed to the same curing conditions. Be sure that concrete with extended set characteristics be protected against excessive water loss due to evaporation prior to set. Although the ECSAs have little direct impact on air entrainment, concrete with extended set may have the tendency to lose air in the extended plastic state.

When used properly to stabilize wash water in a truck mixer or in reclaimer systems, the concrete batched using the treated gray water should have plastic properties very similar to a reference concrete, although the paper by Nakamura and Roberts (1998) does caution the reader on potential issues with air entrainment. If the ESCA is overdosed, it will result in retardation of the concrete. If it is underdosed, the set may be accelerated and the concrete will experience more rapid slump loss than a reference mixture. Typically, the concrete containing ECSA-treated gray water will have higher compressive strengths than a reference mixture of similar water content, even if the ECSA is somewhat underdosed or overdosed. Proper use in stabilization of returned concrete that is then blended with fresh concrete will result in essentially similar properties to reference concrete.

9.7—Effects on hardened concrete

9.7.1 Effect on concrete—Senbeta and Scanlon (1991) discuss test results of concrete in which an ESCA was used and reactivation was carried out after 18 hours of storage. When tested for resistance to freezing and thawing, it gave results comparable to untreated concrete while complying
with ASTM C494/C494M. The same ESCA reported by Senbeta and Scanlon (1991) were studied by Senbeta and Dolch (1991). The effects on the cement paste were evaluated using X-ray diffraction, thermogravimetric analysis, differential thermal analysis, and scanning electron microscopy. The nonexpandable water content, surface area, and pore size distribution were determined. No significant differences were noted between treated and untreated pastes. In an overnight, stabilized returned concrete application, the durability of a stabilized/fresh concrete blended concrete mixture was compared to plain reference concrete (Senbeta and Bury 1992). The durability results from freezing and thawing, petrographic, water absorption, abrasion, susceptibility to cracking, and corrosion tests indicated equivalent to improved performance of the blended mixture relative to the reference concrete. The effect of using these admixtures on compressive strength, tensile strength, flexural strength, air void system parameters, durability, and shrinkage are discussed by Ragan and Gay (1995). No detrimental effects were reported.

9.8—Quality assurance and batching

Trial batches should be run in the laboratory to simulate mixing, transport, and sequence of addition of materials on the day of production.

Further recommended guidelines include:

a) Cylinders that are cast at the site should be conditioned to represent the cast-in-place condition.

b) The dosage of the ESCA should be determined for a range of desired set times under varying temperatures.

c) Extensive pretesting and ongoing monitoring is required for stabilization of returned unhardened concrete.

d) The accelerator dosage to reactivate the stabilized concrete should be related to concrete temperatures and additional fresh concrete.

Both liquid and dry powder versions of ESCAs exist commercially. A liquid solution dispensed through an approved dispensing system is the most controllable and verifiable means to introduce the product. The dry powder versions have the advantage of being easily transportable in a concrete truck where they can be used as needed for emergency situations.

CHAPTER 10—WORKABILITY-RETAINING ADMIXTURES

10.1—Introduction

When portland cement and water are mixed, hydration products begin to form. These hydration products, along with mixing action, create new cement surface areas that are not dispersed, leading to cement agglomeration and workability (slump) loss.

There are several factors that can influence the workability of freshly mixed concrete, including materials, production, and environmental and human factors. The effort required to control workability during delivery and placement may be substantial and costly. Jobsite adjustment of concrete costs the producer in truck time, human resources, and materials.

The act of retempering with water can reduce concrete performance or result in unnecessary overdesign and higher mixture costs to accommodate retempering. A concrete mixture that maintains its fresh properties from the plant to the jobsite will perform better and cost less. The concrete industry has developed several methods for counteracting slump loss, all of which are limited in their effectiveness.

10.1.1 Retemper—Retempering results in an increased w/c that can lower strength and durability, requiring an increased mixture overdesign requirement. The addition of water to air-entrained concrete may change the plastic air content and air void structure, as well as prolong the time a truck is on site by up to 10 minutes per delivery. Site retempering can be particularly problematic if the truck performs insufficient revolutions to completely mix in the added water, which frequently occurs due to time pressure. The addition of water can also influence the setting and bleeding characteristics of the concrete, both of which influence the time when a contractor may begin final finishing operations.

10.1.2 Use of extended set-control admixtures (ESCA)—Also known as hydration-controlling or retarding, these admixtures function by slowing down the rate of portland cement hydration and reducing slump loss. Although in some cases this method could result in unwanted retardation, these admixtures have a successful history of producing the performance desired.

10.1.3 Redose with high-range water-reducing admixture (HRWRA)—Redosing with HRWRA usually requires the concrete producer to deploy quality control staff at the jobsite. Using additional admixture increases the cost per cubic yard (meter) of concrete produced. Similar to the addition of water, redosing with HRWRA may change the plastic air content and prolong the time a truck is on site due to the redosing and retesting process.

10.1.4 Batch to a higher-than-required slump—This technique assumes that the concrete will lose a precise amount of slump during transit and arrive on site within specification limits. This can be difficult to control because of changing materials or environmental conditions. In some instances, to avoid spillage out of the truck during delivery, batching to a higher slump may require the producer to batch less volume per delivery, thereby decreasing delivery productivity. Batching to a very high slump may also cause air control problems.

10.2—Materials

Two types of chemical admixtures are typically used to control workability retention of concrete. One standard practice is using hydration-controlling and retarding admixtures that meet the requirements of ASTM C494/C494M Type B or D to extend slump retention. More recently, a new class of admixtures—neutral set workability-retaining admixtures meeting the requirements of an ASTM C494/C494M Type S—have been commercialized to achieve workability retention using a different mechanism, resulting in some additional benefits.

Hydration-controlling and retarding admixtures have a successful history of improving slump retention. In many
cases, these products provide the performance desired. Retarding and hydration-controlling admixtures function by slowing down the rate of portland cement hydration. Retarding and hydration-controlling admixtures coat the cement grains and slow down the creation of new surface area, thereby delaying agglomeration and slump loss. In some instances, extended setting time and lower early-age compressive strength development may occur, especially when the reason the retarder has been added is not to offset effects of hot weather.

Workability-retaining admixtures provide workability (slump) retention when used in combination with normal, mid-, and high-range water-reducing admixtures (Daczko 2009). This admixture is added separately to the concrete to specifically produce workability retention without impacting initial workability or negatively impacting setting time or early compressive strength. Workability-retaining admixtures allow concrete to maintain its workability and other fresh characteristics throughout the transporting, placing, consolidating, and finishing operations without adversely affecting the time of setting and hardened properties (Daczko 2010). The admixture mechanism continuously supplies a polymer to the surfaces of cement grains to keep them from agglomerating. The workability-retaining admixture allows hydration to continue normally, and adsorbs to any newly created surface area to redisperse it. In mixtures without the admixture, agglomeration and hydration of cement grains result in loss of workability. The workability-retaining admixture maintains cement dispersion until the supply of admixture is exhausted.

10.3—Dosage and effect on fresh and hardened concrete

The fundamental differences between hydration-controlling/retarding and workability-retaining admixtures are slump flow loss profiles and initial setting times of mixtures incorporating either technology. To demonstrate this difference, data collected from three concrete mixtures developed during full-scale production trials are presented (Daczko 2010). These mixtures were targeted to provide 60 minutes of workability retention. Shown are the mixture proportions, product dosages, and initial setting time data comparing traditional retarding and workability-retaining admixtures (Table 10.3a).

The slump flow loss profiles can be seen in Fig. 10.3a. The mixture containing the retarding admixture has the longest setting time (4.9 hours) and a slow rate of slump flow decay after 60 minutes. The mixture containing a moderate dose of workability-retaining admixture provides 60 minutes of slump flow retention and then begins to lose slump flow as structural buildup takes place within the mixture. The mixture containing a higher dose of workability-retaining admixture shows that the slump flow retention can be further extended if desired and when the dispersive effect of the workability-retaining admixture is complete, structural buildup begins and slump flow loss occurs. Note the differences in the profiles between the retarding and workability-retaining admixtures. This feature of a more rapid decay at the prescribed time can be a benefit for wall construction with self-consolidating concrete (SCC), as it can have a significant impact on the formwork pressure. A long, slow decay, as that seen with the retarding admixture, will allow pressure to remain high for an extended period. With the workability-retaining admixture, however, the workability will be maintained during placement, and when placement is complete, a more-rapid structural buildup and reduction in formwork pressure will occur as compared with using retarding admixtures.

Another evaluation was designed to compare the workability-retaining admixture to the technique of using a hydration-controlling admixture (HCA) to extend workability (Daczko 2009). For this evaluation, three identical mixtures were run at 70°F (21°C): a reference mixture with no workability-retaining admixture; a mixture with the workability-retaining admixture; and a mixture with an HCA. The mixtures were non-air-entrained, had the same w/cm, and the cementitious materials consisted of a standard Type I/II cement and Class C fly ash (ACI 232.2R). All mixtures incorporated a lignin-based water reducer at equivalent dosage and a high-range water reducer (HRWR). The HRWR was dosed to achieve an initial slump of 7 to 8 in. (175 to 200 mm).

As shown in Fig. 10.3b, the HCA provided a substantial improvement in the workability retention of the concrete mixture. The workability-retaining admixture, however, provides effective slump retention with minimal impact on the initial time of setting of the concrete mixture (7.5 hours). In contrast, the HCA more than doubled the initial time of setting (14.5 hours). Through the use of workability-retaining admixtures, slump retention without retardation can be achieved.

Increasing the dosage rate of the workability-retaining admixture can increase the amount and duration of slump retention for a given concrete mixture (Fig. 10.3c) (Daczko 2012). Retarding and hydration-controlling admixtures may delay the time of setting and early-age strength development of the concrete mixture. Workability-retaining admixtures generally do not affect the other fresh properties of concrete (Table 10.3b) (Daczko 2010, 2012).

Although it does not typically occur in practice, repeated retempering with water or redosing of high-range water-reducing admixtures (HRWRs) could impact both slump and air content. Slump and air content tend to increase and decrease together. Variability in compressive strength occurs

<table>
<thead>
<tr>
<th>Table 10.3a—Concrete mixture proportions and initial setting time data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mixture</strong></td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Mixture 1</strong></td>
</tr>
<tr>
<td><strong>Mixture 2</strong></td>
</tr>
<tr>
<td><strong>Mixture 3</strong></td>
</tr>
</tbody>
</table>
as water is added and as the air content goes up and down. Compressive strength is less affected by repeated retempering with an HRWRA because the $w/cm$ is maintained.\footnote{DF]NR}

Figure 10.3d demonstrates the impact of the workability-retaining admixture on slump and air content. Relative to retempering and redosing techniques, note that the slump and air contents are much more consistent over time. In addition, the compressive strength is maintained.

![Fig. 10.3d—Workability-retaining admixture’s effect on slump and air content.](image)

### Table 10.3b—Workability-retaining admixture data

<table>
<thead>
<tr>
<th></th>
<th>Mixture 1</th>
<th>Mixture 2</th>
<th>Mixture 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I cement, lb/yd³ (kg/m³)</td>
<td>750 (445)</td>
<td>750 (445)</td>
<td>750 (445)</td>
</tr>
<tr>
<td>$w/cm$</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Polycarboxylate high-range water reducer, fl oz/cwt (mL/100 kg)</td>
<td>8.5 (555)</td>
<td>7.5 (490)</td>
<td>7.5 (490)</td>
</tr>
<tr>
<td>Viscosity-modifying admixtures, fl oz/cwt (mL/100 kg)</td>
<td>5.0 (325)</td>
<td>5.0 (325)</td>
<td>5.0 (325)</td>
</tr>
<tr>
<td>Workability retainer, fl oz/cwt (mL/100 kg)</td>
<td>0</td>
<td>3.0 (195)</td>
<td>6.0 (390)</td>
</tr>
<tr>
<td>Slump flow, in. (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>26.25 (670)</td>
<td>24.50 (620)</td>
<td>24.75 (630)</td>
</tr>
<tr>
<td>30 minutes</td>
<td>26.00 (660)</td>
<td>27.00 (685)</td>
<td>28.50 (725)</td>
</tr>
<tr>
<td>55 minutes</td>
<td>18.00 (460)</td>
<td>24.75 (630)</td>
<td>28.00 (730)</td>
</tr>
<tr>
<td>80 minutes</td>
<td>10.50 (265)</td>
<td>21.00 (535)</td>
<td>27.50 (700)</td>
</tr>
<tr>
<td>Air content, %</td>
<td>1.6</td>
<td>1.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Rate of hardening, h</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>3.6</td>
<td>3.8</td>
<td>4.1</td>
</tr>
<tr>
<td>Final</td>
<td>4.7</td>
<td>4.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Compressive strength, psi (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 hours</td>
<td>2490 (17.2)</td>
<td>2480 (17.1)</td>
<td>2480 (17.1)</td>
</tr>
<tr>
<td>1-day</td>
<td>4640 (32.0)</td>
<td>4790 (33.0)</td>
<td>5330 (36.7)</td>
</tr>
<tr>
<td>7-day</td>
<td>8160 (56.3)</td>
<td>8550 (59.0)</td>
<td>8460 (58.3)</td>
</tr>
<tr>
<td>28-day</td>
<td>9340 (64.4)</td>
<td>9650 (66.5)</td>
<td>10,410 (71.8)</td>
</tr>
</tbody>
</table>

#### 10.4—Applications

Extending the workability retention of concrete may greatly enhance the performance of concrete by making the placing, consolidating, and finishing processes more predictable and efficient. Workability-retaining admixtures are used in a variety of applications as follows in 10.4.1 through 10.4.8.

**10.4.1 Low-w/cm, high-performance concrete**—Concrete with a low $w/cm$ tends to be sticky, and workability retention can minimize placement, consolidation, and finishing issues. By ensuring the workability retention of such mixtures, placement challenges are reduced, resulting in improved and consistent in-place quality and faster job completion.
10.4.2 Self-consolidating concrete—Self-consolidating concrete (SCC) (ACI 237R) is expected to be placed without consolidation energy and, therefore, should arrive on site with the desired workability level. SCC should also retain sufficient workability to ensure meshing of subsequent deliveries. Rapid stiffening and workability loss during placement are unacceptable for this type of concrete.

10.4.3 Projects with slower or discontinuous placement techniques—When using a crane and bucket for concrete placement, a single delivery of concrete can typically fill a bucket three to four times. This requires the concrete to maintain its workability for a longer period of time to ensure ease of placement and consolidation, as well as consistent in-place properties.

10.4.4 Sustainable concrete mixtures using high amounts of supplementary cementitious materials—When using high cement replacement levels of supplementary cementitious materials (SCMs) (4.2) and expecting acceptable concrete performance, retempering is highly undesirable. Workability retention is key to ensuring performance in the fresh and hardened states.

10.4.5 Fast-track, high-early-strength concrete—Rapid-strength-developing concrete (for example, 3000 psi [20 MPa] in 4 hours) tends to have a shorter placement window. Providing workability retention without retardation improves ease of use for this type of concrete.

10.4.6 Floors with floor flatness requirements—A uniform and consistent slump from batch to batch is essential to achieving strict floor flatness requirements (ACI 302.1R).

10.4.7 Fiber-reinforced concrete—When fibers are added to concrete, workability can be influenced. Extending the workability retention time without retardation can make the placement and handling of fiber-reinforced concrete more acceptable to the contractor.

10.4.8 Precast/prestressed concrete—Production and placement efficiency, high-early compressive strength, and a high-quality as-cast surface finish are important to precast/prestressed producers. Achieving the necessary level of workability, and then maintaining it for the time needed for placement and consolidation, is critical. For precast production, the amount of workability retention time required may vary depending upon the project or plant. By maintaining concrete workability without retardation, and thereby achieving higher early compressive strength, the precast producer can optimize production. The use of a workability-retaining admixture may also result in fewer surface quality issues, such as pour lines or surface air voids resulting from premature concrete stiffening.

10.5—Quality assurance and batching

Workability-retaining admixtures are typically batched and dispensed as liquids. They should be batched following the manufacturer’s recommendations. Storage tanks for admixtures should be clearly identified and the solutions protected from contamination, dilution, evaporation, and freezing.

CHAPTER 11—VISCOSITY- AND RHEOLOGY-MODIFYING ADMIXTURES

11.1—Introduction

Viscosity-modifying admixtures (VMAs) are typically water-soluble polymers used in concrete to modify its rheological properties. Rheology is the science dealing with deformation and flow of materials, whereas viscosity refers to the resistance of motion under an applied force. VMAs influence the rheology of concrete by increasing its plastic viscosity; the effect on yield stress widely varies with the type of VMA, from no increase to a significant one. Plastic viscosity is defined as the property of a material that resists change in the shape or arrangement of its elements during flow, and the measure thereof, and yield stress is defined as the critical shear stress value below which a viscoplastic material will not flow and, once exceeded, flows like a viscous liquid.

In concrete, the use of VMAs increases the robustness of concrete mixture, helps to improve its quality control, and enhances its surface finish. The rheology of fresh concrete is primarily described by its yield stress and plastic viscosity. For more information on rheology and plastic viscosity refer to 18.2.1.

Over the last few decades, as concrete technology, production, materials, and demands have changed, there has been an increase in the use of highly workable concretes, as well as materials that previously were considered less desirable for use. Concrete is a composite material having particles of different sizes and aggregates with varying moisture contents. One of the challenges to producing a highly workable concrete is holding all the concrete constituents together, without segregation from its production to its placement. The use of gap-graded aggregates and manufactured sands also contribute to this challenge. Together, these issues have led to VMA use in concrete. VMAs are commonly used in self-consolidating, highly workable, and pervious concrete, as well as concrete containing gap-graded aggregates. Some of the raw materials used for VMAs are also used in anti-washout admixtures (AWAs), which are discussed in 11.7.

11.2—Materials

Materials commonly used as viscosity-modifying admixtures (VMAs) are polyethylene oxides, cellulose ethers (hydroxyethyl cellulose and hydroxypropyl methylcellu-lose), alginites (from seaweed), natural and synthetic gums, and polyacrylamides or polyvinyl alcohol. Other materials used are finely divided solids such as starches, clays, lime, and polymer emulsions.

11.3—Selection and evaluation

Viscosity-modifying admixtures (VMAs) should be selected by conducting trial mixtures with the actual concrete materials being used to produce the concrete under the same environmental conditions. VMAs are commonly used in self-consolidating concrete (SCC), as described in ACI 237R. ACI 237R describes three approaches for developing SCC mixtures:
11.4—Applications

There are several benefits of using viscosity-modifying admixtures (VMAs) in concrete. VMAs are commonly used in self-consolidating concrete (SCC), high-slump, or flowable concrete to minimize bleeding and segregation. In SCC mixtures, even a small variation in the moisture content of the aggregates can affect the cohesion of the mixture. Use of VMAs makes the mixture robust and tolerant to variations in the water content. Viscosity-modifying admixtures also allow for a reduction in the total cementitious content of an SCC mixture. For these highly flowable mixtures, form pressure can become an issue. Increased thixotropy by the use of a VMA can be helpful in reducing form pressure (18.2.1).

VMAs are also used in concrete containing gap-graded aggregates, or when the fine aggregates lack sufficient amount of fines. In addition, these products work well for use with manufactured sands that exhibit high bleed and poor finishability. Pervious concrete, which contains little to no fine aggregates, also benefits from VMAs. In these cases, the admixture helps to stabilize the mixture, making the cement paste more robust and less likely to separate from the coarse aggregates.

VMAs are also used in pumped concrete. In pumped concrete, high pump pressures can separate the mortar fraction from the concrete mixture. This can lead to agglomeration of coarse aggregates that can block the line. Use of VMAs make the mixture cohesive and prevents chocking of the pump.

11.5—Dosage and proportioning concrete

Viscosity-modifying admixtures (VMAs) are a poten tool for adjusting the rheological properties of concrete mixtures to improve it. For SCCs, consider VMAs during the mixture design to optimize the total cementitious or fines content. Addition of VMAs usually does not require making any significant changes in the mixture proportioning. The dosage of VMA required to achieve the desired rheological proper-

ties should be determined by trial mixtures, starting from the manufacturer’s recommendations or from experience. With some VMAs, an increased dosage of high-range water-reducing admixture (HRWRA) is needed to compensate for the loss of flow from the binding action of the VMA.

11.6—Effects of fresh and hardened concrete

Overall, viscosity-modifying admixtures (VMAs) help to improve the plastic and hardened properties of concrete. Although some VMAs have an increasing effect on the yield stress value, most high-molecular-weight, water-soluble polymers described previously and used in these products increase the viscosity or thicken the interstitial water. Such compounds increase the cohesiveness of fresh concrete, reducing its tendency to segregate and bleed. These admixtures are also helpful in improving the properties of lean concretes with low cement contents or gap-graded aggregates. They also provide body to the mixture, giving improved finishing characteristics and better pumpability. For pumpability, they reduce pumping pressure through improved lubricating properties and decreased segregation tendencies. For this reason, they are also often used as pumping aids. Common applications for these products are grouting, post-tensioning and injection, oil field cement, and self-consolidating concrete (SCC). Increased thixotropy from the use of VMAs is potentially helpful in reducing form pressure. Some VMAs at higher dosages can increase the setting time of concrete.

In the hardened state, VMAs have been shown to improve air void structure and surface appearance. In general, most VMAs do not have any significant effect on the compressive strength of concrete.

11.7—Anti-washout admixtures

Anti-washout admixtures (AWAs) increase the cohesiveness and improve the self-leveling characteristics of concrete to be placed under water by pumping. The most common AWAs are based on natural or synthetic gums and cellulose-based thickeners. Silica fume (ACI 234R) can also be beneficial in enhancing cohesion. Loss of cementitious material due to washout can be reduced by as much as 50 percent by the inclusion of an AWA (U.S. Army Corps of Engineers 1994). Compatibility between other admixtures and AWAs should be tested, as excessive amounts of air have been observed. Most natural gum-based AWAs retard setting time up to 24 hours at high dose rates, and most AWAs eliminate bleeding (Neely 1988). AWAs bind the constituents of the concrete together and prevent the concrete from segregating. The binding action of the AWAs can reduce the workability of the concrete. In such cases, to maintain the same w/cm, the dosage of the high-range water-reducing admixture (HRWRA) should be increased to achieve the desired workability.

11.8—Rheology-modifying admixtures

In 2008, a new rheology-modifying admixture (RMA) was reported by Bury and Bury (2008). Rheology-modifying admixtures are admixtures that affect the flow characteristics...
CHAPTER 12—SHRINKAGE-REDUCING AND SHRINKAGE-COMPENSATING ADMIXTURES

12.1—Introduction

Shrinkage in concrete and mortar occurs in three basic modes: plastic, autogenous, and drying. Plastic shrinkage occurs before final set due to the rapid evaporation of bleed water from the exposed surface of the concrete. Autogenous shrinkage is the change in volume under constant temperature and without loss of moisture from the concrete to the environment (Tomita 1992), and originates from reduction of the relative humidity in the pores as the hydration of the cement occurs (Berke et al. 1997; Shoya et al. 1990). Most autogenous shrinkage deformation occurs in the course of the first 7 days after casting. Drying shrinkage occurs after final set due to a reduction in volume caused by the evaporation of water from the concrete pores. For high-strength concretes, drying shrinkage, and particularly autogenous shrinkage, are the most detrimental because they increase the potential for severe cracking. Autogenous shrinkage is less significant than drying shrinkage for normal-strength concrete (less than 5000 psi [34 MPa] in 28 days). The susceptibility of concrete to cracking due to drying shrinkage depends on whether the concrete is restrained or unrestrained. Because most concrete is restrained by subgrades, foundations, reinforcement members, or connecting members, it often develops tensile stresses high enough to cause cracking.

One measure taken to reduce shrinkage cracking is the use of high-range water-reducing admixtures (HRWRAs) to attain a very low w/cm and reduced cement contents. Particle gradation, which optimizes the ratio of fine and coarse aggregates, has also been shown to help reduce shrinkage. Another method to alleviate the effect of shrinkage is the use of shrinkage-reducing admixtures (SRAs) and shrinkage-compensating admixtures (SCAs). SRAs reduce the surface tension of water capillaries and SCAs cause an expansive reaction to compensate for the volume lost during drying and autogenous shrinkage. SRAs were introduced in Japan in 1985 and to the North American market in 1995. SRAs reduce the capillary tension of the pore water pressure without expansion. They should be monitored for strength loss, rapid set, and loss of workability. Various SCAs have been used in the past and continue to be formulated. When hydrated, some SCAs form ettringite products that take up more volume than the original components, which can lead to expansion that can counteract autogenous and drying shrinkage when used correctly. The quality of SCAs should be monitored carefully, as they tend to have a great range of consistency and effectiveness. Calcium sulfoaluminate- and calcium aluminate-based SCAs were used in the past, but achieving consistent results was challenging; take care to avoid uncontrolled expansion with these materials. Calcium hydroxide (lime-based) materials have also been used to reduce shrinkage cracks. Magnesium oxide, which has been used in dam construction in China for several decades, recently gained acceptance in North America due to its ability to expand at a rate closely matching the drying shrinkage of concrete (Du 2005; Bureau of Reclamation...
12.2—Materials

Shrinkage-reducing admixtures (SRAs) are typically composed of polyoxyalkylene alkyl ether or similar composition. According to published patents, the general composition of the SRA is indicated as R1O(AO)mR2, where A is an alkyl group having a carbon chain number of 2 to 4 or two different types of alkyl groups. R1 and R2 are selected from the hydrogen, hydroxyl, alkyl, phenyl, and cycloalkyl groups. The variable n is an integer between 2 and 10, indicating the degree of polymerization (Tomita 1992). Most commercially-available SRAs are a glycol ether blend (Berke et al. 1997; Rixom and Mailvaganam 1999; Bentz et al. 2001).

Many types of shrinkage-compensating admixtures (SCAs) have been used, including calcium sulfoaluminate or calcium-aluminate-based systems, calcium hydroxide formation (lime-based system), and magnesium oxide systems. Magnesium oxide behavior will vary depending on the quality and the heat of calcination. In general, high-quality lightly burnt (1100 to 1475°F [600 to 800°C]) is most successful in compensating for concrete drying and autogenous shrinkage without deleterious effects on the concrete. Success has also been achieved when using a hybrid material that combines SRAs to reduce the pore water tension and SCAs, specifically lightly burnt magnesium oxide, to provide a controlled expansion.

12.3—Mode of action

The driving force for drying shrinkage is volume-reduction that occurs due to the evaporation of water from capillary pores in hydrated cement paste at the surface, which are exposed to air with a relative humidity lower than that within the capillary pores. The water in the capillary pores, called free water, is held by forces that are stronger the smaller the diameter of the capillary pore. It is only when the tensile stress induced in the hydrated cement paste by the capillary forces exceeds the local tensile strength of the concrete that cracks occur (Aitcin et al. 1997).

Capillary tension theory—a theory that explains the mechanism of drying shrinkage—states that one main cause of drying shrinkage is the surface tension developed in the small pores of the cement paste of concrete (Berke et al. 1997). When these pores lose moisture through evaporation, a meniscus forms at the air-water interface. Surface tension in the meniscus pulls the pore walls inward; the concrete shrinks as a result of these internal forces. This shrinkage mechanism occurs only in pores within a fixed range of sizes. Although the amount of cement-paste shrinkage caused by surface tension depends primarily on the w/cm, it can also be affected by cement type and fineness, and by other ingredients such as admixtures and supplementary cementitious materials, which affect pore size distribution in the hardened paste.

The shrinkage-reducing admixture (SRA), which reduces shrinkage by reducing the surface tension of water in the pores, is dispersed in the concrete during mixing. After the concrete hardens, the admixture remains in the pore system where it continues to reduce the surface tension effects that contribute to drying shrinkage. In both laboratory and field tests of various concrete containing the admixture, the product seemed to be most effective when added at a rate of 1.5 to 2.0 percent by weight of cement (Tomita 1992; Berke et al. 1994). Dosages of 1 to 2.5 percent, however, can be used to obtain the desired level of shrinkage without adverse side effects (Rixom and Mailvaganam 1999; Bentz et al. 2001).

Capillary tension within the pore system may also contribute to self-desiccation of the concrete member. Without the use of an SRA, wick action through the finer pores can draw water from the larger pores within the concrete member to the surface, increasing the rate of evaporation. By reducing the capillary tension of the pore water by using an SRA, self-desiccation is reduced. This allows the water to continue curing the concrete, leading to less drying shrinkage cracks (Bentz 2005).

12.4—Applications

Shrinkage reduction is highly advantageous in many applications, such as architectural precast, pneumatically-applied concrete; water-retaining structures; and for most horizontal slab applications such as floors, roofs, and parking decks. The capacity for minimizing cracking, thereby potentially allowing a reduction in contraction joints, and the reduction in curling makes the shrinkage-reducing admixtures (SRAs) and shrinkage-compensating admixtures (SCAs) ideally suited for slab applications. In structures where water leakage is a problem, the use of these admixtures can result in the reduction of the number of cracks. SRAs are reported to reduce the loss of prestress in prestressing applications (Nmai et al. 1998b). SRAs and SCAs are also used to offset the effects of certain high-shrinkage aggregates (Holland 1999). For this application, a comparison of the cost of the SRA or SCA with the cost of obtaining a better aggregate should be determined. SCAs, specifically magnesium oxide, have been used in dam construction due to its ability to reduce shrinkage cracks. Significant shrinkage crack reduction, up to 90 percent, has been observed when using a hybrid admixture that combines a glycol ether blend SRA with a magnesium oxide SCA (Westin 2011).

12.5—Dosage and proportioning concrete

Adding the shrinkage-reducing admixture/shrinkage-compensating admixture (SRA/SCA) after all other admixtures have been introduced into the mixture is recommended. As the dosage of an SRA is increased within the recommended dosage range, the drying shrinkage decreases. Trial mixtures adjusting the amount of cement, aggregate, and SRA/SCA should be conducted to determine the optimal
mixture proportions required to meet the desired shrinkage. SRAs can interact with air-entraining agents that destabilize the concrete air content. Trial mixes should also be run to verify fresh concrete characteristics.

12.6—Effects on fresh and hardening concrete

Although the primary impact of shrinkage-reducing admixtures/shrinkage-compensating admixtures (SRAs/SCAs) is to reduce autogenous and drying shrinkage, the admixture may also affect other fresh properties of the concrete. When an SRA is added at a dosage of 2 percent by mass of cement to the concrete mixture without an adjustment for the volume of the water introduced by the admixture, the concrete’s slump is increased. When substituted for an equal volume of water, however, the SRA has little to no effect on slump. Some SRAs may have a slight retarding effect on the rate of hydration and extend the setting time up to approximately 1 hour (Nmai et al. 1998b). The SRA may affect the air content and the air void distribution or parameters of fresh concrete and, therefore, when used in air-entrained concrete, the dosage of the air-entraining admixture often needs to be increased to achieve a proper spacing factor. As with all concrete mixtures, each mixture containing SRAs or SCAs should be evaluated for fresh concrete properties such as proper workability, finishability, and setting time by conducting a successful test placement.

12.7—Effects on hardened concrete

12.7.1 Drying shrinkage—The amount of shrinkage reduction depends very much on the ambient conditions (temperature and relative humidity), mixture design, and the materials used. Generally, a reduction of 30 to 50 percent shrinkage measured by length change can be achieved. Although higher percentages of reduction have been achieved with specific materials and mixture designs, it is important to evaluate a given set of materials to make recommendations on dosage and performance. Magnesium oxide-based SCAs have been shown to reduce drying shrinkage cracks by up to 90 percent (Westin 2011).

12.7.2 Compressive strength—Previous work has shown that adding some SRAs to concrete at a 2 percent dosage by mass of cement can reduce the strength as much as 15 percent at 28 days (Balogh 1996; Shoya et al. 1990). In general, the strength reduction is less in concretes with a lower w/c. Strength reduction can be counteracted by lowering the w/c using a high-range water-reducing admixture (HRWRA), slightly reducing the SRA dosage, or both (Nmai et al. 1998b). Some manufacturers recommend the addition of enough HRWRA to reduce the mixing water by a minimum of 10 percent while keeping the cement content constant (Berke et al. 1994). Magnesium oxide-based SCAs could have an effect on the compressive strength of concrete when used as a cement replacement. When magnesium oxide-based SCAs are used in as an addition to cement, no significant effect on the compressive strength has been documented. When using SCAs in low-w/c mixtures (less than 0.38), additional water should be added due to an increased water absorption by the magnesium oxide. When an increase in slump is desired, it should be achieved by the use of a high-range water reducer (HRWR).

12.7.3 Curling—The curling of concrete slabs is caused by the top surface drying and shrinking faster than the core concrete. In laboratory testing with 8 x 4 ft (2.44 x 1.22 m) slab specimens, SRAs showed a significant tendency to reduce curling of the slab. This property of the admixture was confirmed in a field trial conducted by the Virginia Department of Transportation, where 1.5 gal./yd3 (7.35 L/m3) was used in a test overlay for the Lesner Bridge (Berke et al. 1994).

12.7.4 Air-void parameters, freezing-and-thawing resistance, and salt scaling resistance—Generally, concrete mixtures containing 6 percent air or more will have adequate spacing factors and will therefore be resistant to cyclic freezing, especially in the presence of deicing salts. However, surfactants used in some SRAs, even though yielding proper spacing factors, cause the concrete to readily attain saturation, rendering it more susceptible to freezing-and-thawing attack. It is possible that these surfactants are acting as wetting agents and promoting the inhibition of water into the concrete, causing two potential problems:
1) Freezing-and-thawing damage because of a saturated top surface, even though the air void spacing is correct
2) The concrete is susceptible to freezing-and-thawing damage if the SRA adversely affects the air void system

Trial mixes are recommended to ensure proper air void spacing to resist this type of exposure.

12.8—Quality assurance and batching

Shrinkage-reducing admixture (SRA) or shrinkage-compensating admixture (SCA) dosage and post-placing curing conditions affect the shrinkage properties of concrete and, hence, the selection of an appropriate dosage would depend on the level of shrinkage desired, the degree of set retardation that is acceptable, and curing conditions. Proper quality-control procedures should be implemented to minimize the occurrence of differential expansion. Proper placing and curing procedures are critical for applications where SRAs or SCAs are being used. SRAs and SCAs should be batched following the manufacturer’s recommendations.

CHAPTER 13—CORROSION-INHIBITING ADMIXTURES

13.1—Introduction

Steel in concrete is normally protected from corrosion by the high pH of the concrete environment, which creates a stable passivation layer of iron oxides and hydroxides on the steel surface. Chlorides, however, can penetrate this layer and soluble iron chloride complexes form that weaken this layer due to the increased solubility of the iron. These allow iron to migrate from the bar surface outward in the cement paste, which leads to active ongoing corrosion of the steel.

Other causes of corrosion of steel in concrete are carbonation, galvanic attack between dissimilar metals, and stray current corrosion from external sources of direct current (ACI 201.2R; ACI 222R). While corrosion inhibitors for steel in concrete are generally tested with chlorides, and
some have been evaluated for carbonation-induced corrosion, there is little if any literature on their effectiveness in the presence of stray current or galvanic corrosion.

Corrosion reduces the cross-sectional area of the reinforcing steel and often leads to spalling of the concrete over it because of increased volume of the corrosion products. For these reasons, admixtures that mitigate the corrosion process are useful in extending the life of concrete structures, sometimes by themselves or in conjunction with other techniques to limit the intrusion of chlorides.

Corrosion inhibitors are described in ACI 222R as admixtures that will either extend the time to corrosion initiation or significantly reduce 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.

In evaluating corrosion inhibitors, in some accelerated tests, the chloride intrusion rate can be so quick that samples just going into corrosion are found to have higher chloride ion concentrations because the concentration rises so quickly that the actual initiation concentration is exceeded. For this reason, highly accelerated testing is inappropriate for determining corrosion thresholds both with and without corrosion inhibitors. Such tests, however, can be used to demonstrate that a given material is an inhibitor.

According to ASTM C1582/C1582M, for a material to be considered a corrosion inhibitor, it must show reduction in corrosion rate and corroded area of bars in concrete containing chloride at a level above the level that induced corrosion in the reference test specimens. As the methods are accelerated, they indicate only that the admixture is a corrosion inhibitor, and not the level of corrosion protection provided in service. Techniques or materials that reduce the actual intrusion of chloride, while being useful, are not corrosion inhibitors. Most corrosion protection systems employing corrosion inhibitors also use various methods to reduce chloride intrusion to be efficient in the use of the corrosion inhibitor, and combine this with a conservative depth of concrete over the reinforcement. These methods may include, but are not limited to, reducing the w/cm, inclusion of various supplementary cementitious materials (SCMs) that reduce permeability, and the use of a variety of organic materials that restrict wetting. An advantage of corrosion inhibitors lies in their ability to extend time-to-corrosion without requiring an extreme reduction in permeability, because systems that attempt to protect against corrosion entirely by restricting chloride ingress may have problems with placement because of rheological properties, early-age cracking (high silica fume contents and very low w/c), requirement for extended curing (high pozzolan levels), or restricted strength development at early ages (high pozzolan and slag). Some of these effects may reduce the actual corrosion protection afforded, especially if cracking results. Therefore, the use of moderate levels of corrosion inhibitor with moderate levels of permeability reduction from SCMs may result in the needed protection while resulting in concrete that is easier to place (Berke et al. 2005). Corrosion inhibitors that intrinsically reduce the permeability of the concrete also may provide this protection without the need of supplementary materials.

13.2—Materials
Many chemicals have been evaluated in the past as potential corrosion-inhibiting admixtures for concrete (Verbeck 1975; Clear and Hay 1973; Griffin 1975; Berke 1989). These include chromates, phosphates, hypophosphites, alkalis, nitrites, and fluorides. Three corrosion-inhibiting admixtures are supported commercially at the present time: amine carboxylate; amine-ester organic emulsion; and calcium nitrite. Amine derivatives have been used commercially as corrosion inhibitors in the United States since the mid-1980s and have an extensive track record in both laboratory and field studies. They are generally available as concentrated liquids or powders. The latest versions of amine derivative corrosion inhibitors are based on a synergistic blend of amine carboxylates with the addition of metal salts of carboxylic acids and nonorganics, which are referred to as amine carboxylates.

Amine carboxylates are classified as mixed inhibitors, meaning they affect both anodic and cathodic portions of the corrosion cell. Each amine carboxylate molecule is a dipole and has positive and negative charges that are attracted to the anodic and cathodic portions of a corrosion cell. These inhibitors adsorb onto metal, forming a protective molecular layer on steel surfaces (Fig. 13.2a). This film prevents corrosive elements from further reacting with embedded reinforcement, and also reduces existing corrosion rates. Adsorption of the inhibitor onto the metal through its polar functional group takes place with the nonpolar or hydrophobic chain of the inhibitor molecule oriented perpendicular to the metal surface. The hydrophobic chains not only repel aqueous corrosive fluids, but interact with each other to form aggregates, thereby forming a tight film on the metal surface (Sastri 1998).

Amine carboxylates reach embedded reinforcement in several ways. First, the inhibitor is dispersed through the concrete with adequate mixing. Second, the amine carboxylate inhibitors have a vapor pressure that allows them to migrate through the pore structure of the concrete in a gaseous state. The molecules move randomly from areas of high concentration to areas of low concentration until equilibrium is reached (Fick’s Second Law). Finally, when the molecules come in contact with embedded metals, they have a specific ionic attraction to it. The positive and negative charges within amine carboxylate molecules are attracted to anodic and cathodic microcells on the metal surface, forming a protective, monomolecular layer that also reduces the corrosion rate (Bavarian and Reiner 2004). As amine carboxylates migrate through the concrete, some of them will react with calcium hydroxide in the concrete to form calcium oxalate [Ca(COO)₂], an insoluble salt, which effectively blocks some of the pores, making future ingress of chlorides and other contaminants more tortuous (Sastri 1998).

The amine-ester organic corrosion inhibitor has been used commercially since 1990 and it is available as a milky-white emulsion. It consists of fatty-acid esters and amines (Nmai
et al. 1992) and surfactants that provide stability to the emulsion as well as enhance corrosion-protection performance. This organic corrosion inhibitor provides protection against chloride-induced corrosion of steel in concrete via a twofold mechanism that involves the formation of a protective film on the steel surface and a reduction in chloride permeability of the concrete (Nmai et al. 1992).

When the amine-ester organic inhibitor is first added to concrete, the esters become hydrolyzed by the alkaline mixture water to form carboxylic acid and its corresponding alcohol. This reaction, under alkaline conditions, is favorable and is not easily reversed (Carey and Sundberg 1984). The reaction proceeds (Eq. (13.2)), where R and R’ represent different hydrocarbon molecules.

\[
\text{RCOOR’} + \text{OH}^- \rightarrow \text{RO}^- + \text{R’OH}
\]

The carboxylic anion is quickly converted in concrete to the insoluble calcium salt of the fatty acid (Carey and Sundberg 1984). The fatty acids that are formed and their calcium salts provide a hydrophobic coating within the pores that causes a reversed angle of contact in which the surface tension forces now push water out of the pore instead of into the pore (Ramachandran 1995). The hydrophobic calcium salt lining also reduces the diameter of the pores, thus reducing the migration of water and attendant contaminants through the capillary pore matrix. After the concrete mixture is placed, the key components of the amine-ester organic inhibitor are adsorbed onto the surface of the reinforcing steel to form a protective film. Simplistically, the film-forming amine (FFA) component, which can be described most effectively as a surface-acting chelants (Bobrowski and Youn 1993; Buffenberger et al. 2000), bonds with the steel and the fatty-acid esters chain over the nonpolar tails to form a tight mesh (Fig. 13.2b) that restricts moisture, chloride, and oxygen availability at the steel surface. Hence, the organic corrosion inhibitor functions as a mixed inhibitor, affecting the anodic reaction by raising the chloride threshold for corrosion initiation and the cathodic corrosion reaction by restricting moisture and oxygen availability.

The film-forming mechanism by which the amine-ester organic inhibitor inhibits corrosion is the same mechanism by which other organic corrosion inhibitors function, that is, by adsorption on the metal surface. In addition, this barrier may be enhanced by the ability of the hydrophobic tails of the chelated FFA to attract other hydrocarbon molecules, such as additional FFA molecules or the waterproofing ester, to create an additional water-repellent oil film (Nathan 1973). The hydrophobic lining of the pores and the protective film at the steel surface created by the amine-ester organic inhibitor are formed immediately after concrete placement and are very stable (Bobrowski and Youn 1993; Buffenberger et al. 2000). The organic corrosion inhibitor will not migrate through the concrete matrix and will allow only miniscule leaching.
taining the same concentration of nitrite. An example of the impact of the material on corrosion at variable dosage rates is shown in Fig. 13.2c.

13.3—Selection and evaluation

Corrosion inhibitors for chloride-induced corrosion can be evaluated according to ASTM C1582/C1582M, which provides two methods to demonstrate the performance. As the methods are accelerated, they indicate only that the admixture is a corrosion inhibitor, but not the level of corrosion protection provided in service.

Due to the economic trade-offs necessary between inhibitor dose, cost of reducing the w/c, costs of increasing reinforcing steel cover, the differing costs of pozzolans, and cost of future repair, several of the models allow cost inputs and trade-off analyses of alternative design approaches in terms of net present value of each approach.

The dosage rate of amine carboxylates is independent of the expected chloride levels. The recommended dosage rate is a sufficient concentration of inhibitor to form a monomolecular film on embedded metals and that dosage rate is not dependent on chloride concentrations.

The recommended dosage of the amine-ester organic corrosion inhibitor for protection of steel in concrete is 1 gal/yd³ (5 L/m³). This dosage is optimized to provide effective corrosion inhibition while minimizing the impact of the inhibitor on the fresh and hardened properties of concrete; in particular, air entrainment and compressive strength. Synergistic reduction in chloride ingress is obtained when the amine-ester organic inhibitor is used in combination with silica fume and, by extension, other permeability-reducing supplementary cementitious materials (SCMs), as shown by the data in Fig. 13.3a. The data were obtained from chloride profile tests performed on specimens exposed to the marine environment at the U.S. Army Corps of Engineers Treat Island Weathering Station for a period of 7 years (Miller and Miltenberger 2001). Therefore, for severe corrosion environments, the use of the amine-ester organic inhibitor or other corrosion inhibitors is recommended for use in combination with SCMs, a low w/cm (less than or equal to 0.40), and adequate clear cover over steel.

Calcium nitrite is not a product with one set dosage. The dose can be adjusted to match the durability and life-cycle cost requirements of the structure being considered. Increasing the dosage of calcium nitrite will protect steel from corroding for longer periods of time by protecting against higher concentrations of chloride that permeate into the concrete, as detailed in Table 13.3. The prediction of the chloride concentrations in concrete at the reinforcing bar level as a function of time is a process that has been well researched and published over the last 10 to 15 years (Berke et al. 1998, 2005; Berke and Hicks 2004; Samson and Marchand 2006). These chloride ingress prediction models vary from relatively simple ones based on Fick’s Law of Diffusion (Berke et al. 1998; Ehlen et al. 2009) to more complex ones, including capillary suction and chem-
13.4—Applications

Amine carboxylate-based admixtures are appropriate to use for reducing chloride-induced corrosion of any high-quality concrete, from seawater, salt-laden air, and deicing salt exposure. They are also effective in reducing corrosion due to carbonation, or combinations of the two (Xu et al. 2004).

The amine-ester organic corrosion inhibitor is recommended for use in extending the service life of steel-reinforced concrete structures exposed to chlorides in service. In accordance with code requirements, it has to be used in high-quality concrete with a maximum w/cm of 0.40 and an appropriate level of clear cover over the reinforcing steel. It has, however, also been shown to provide effective corrosion protection for steel in concrete at a w/cm of up to 0.50 because of its effectiveness in reducing chloride ingress under cyclic wetting-and-drying exposure conditions (Nmai and McDonald 2000).

Calcium nitrite is appropriate to use for reducing chloride-induced corrosion of any high-quality concrete, from seawater, salt-laden air, and deicing salt exposure. It is not applicable for low-quality concrete or concrete with very low clear cover over the reinforcing steel, as in those situations the chloride levels build so rapidly that the protection from calcium nitrite lasts an uneconomically short time.

13.5—Dosage and proportioning concrete

General guidelines for proportioning good concrete mixtures are applicable to mixtures containing corrosion-inhibiting admixtures. Because durability in a corrosive environment is the reason for the use of these admixtures, a low w/c is advisable. The type of admixture, the environment, and the design life of the structure (along with other factors), however, will dictate the proportioning of the mixture. Guidance is presented in the following.

The standard dosage rate for amine carboxylates is 1.0 to 1.5 pt/yd³ (0.6 to 1 L/m³) for liquids and 1 lb/yd³ (0.6 kg/m³) for powder versions. Amine carboxylates can be added with the mixture water to concrete at a concrete plant, or added on the jobsite as a powder. They are generally compatible with the use of pozzolans or slag (ACI 232.1R; ACI 232.2R; ACI 233R) and do not affect the finishing properties of the concrete when used in combination with them. Because the dosage rate is so low, there is no need for adjustments to the mixture design.

For the amine-ester organic inhibitor, proportioning in accordance with ACI 318 for concrete that would be exposed to chlorides in service is appropriate. ACI 318 requires a maximum w/cm of 0.40 and a minimum compressive strength of 34.5 MPa (5000 psi). In most applications, the compressive strength achieved with the use of such a low w/cm would exceed the specified strength. Consequently, a modification in mixture proportions may not be required to compensate for the marginal decrease in compressive strength that can occur with the use of the amine-ester organic inhibitor. If desired, or if the decrease in compressive strength is unacceptable, the w/cm of a mixture treated with the amine-ester organic corrosion inhibitor should be reduced slightly to offset the strength decrease.

For calcium nitrite, generally permeation and economic modeling shows that concrete should be proportioned at a w/c of 0.40 or less, although moderate-design-life concretes

<table>
<thead>
<tr>
<th>Chloride ion, lb/yd³ (kg/m³)</th>
<th>Calcium nitrite 30 percent solution, gal/yd³ (L/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 (3.6)</td>
<td>2 (10)</td>
</tr>
<tr>
<td>9.9 (5.9)</td>
<td>3 (15)</td>
</tr>
<tr>
<td>13 (7.7)</td>
<td>4 (20)</td>
</tr>
<tr>
<td>15 (8.9)</td>
<td>5 (25)</td>
</tr>
<tr>
<td>16 (9.5)</td>
<td>6 (30)</td>
</tr>
</tbody>
</table>
can be achieved with a w/c of 0.45 with a pozzolan or slag (ACI 233R).

High-range water-reducing admixtures (HRWRAs) are used to achieve the required w/cm without requiring an increase in cementitious content. Due to the permeability-reducing benefits of slag and pozzolans, dosage rates of calcium nitrite above 4 gal/yd$^3$ (20 L/m$^3$) are unusual (Berke and Rosenberg 1989), as long as pozzolans or slag are available, cover is adequate, and design service lives are not extreme. Calcium nitrite requires high volumes of product to attain results, as high as 6 gal/yd$^3$ (30 L/m$^3$).

This volume should be accounted for in mixture proportions: for the typical 30 percent calcium nitrite solution, approximately 85 percent of the volume is water. Take care to ensure that the calcium nitrite is added separately from other admixtures, preferably near the completion of the batching sequence. Some problems were encountered in the early use of calcium nitrite when the strength requirements of concrete design and w/c required for permeability control were incompatible. That is, a design strength of, for example, 30 MPa (4350 psi) was required, but a w/c of 0.37 cited. While proper following of mixture proportioning principles of ACI 211.1 would identify that the w/c was controlling, in some cases, producers tried to take standard mixtures and drive down the w/c with artificially high levels of high-range water reducer. This led to high slump loss and control issues indirectly related to the calcium nitrite.

### 13.6—Effects on fresh and hardening concrete

Amine carboxylates can retard setting times 3 to 4 hours at 70°F (20°C); however, normal set versions containing an accelerator so that they set similarly to a control (mixture with no amine carboxylate) are available. These generally have little effect on the early fresh properties of concrete, as long as proper mixture proportioning has been followed. Testing should be done when amine carboxylate-based admixtures are used together with lignin or naphthalene sulfonate HRWRAs to establish that the setting time is acceptable. To avoid this problem, use melamine or polycarboxylate-based HRWRAs when using amine carboxylate-based corrosion inhibitors.

The amine-ester organic corrosion inhibitor generally has little effect on the fresh and plastic properties of concrete, including time of setting. Depending on mixing efficiency and the characteristics of a mixture, however, an increase in the dosage of air-entraining admixture and additional mixing or a change in batching sequence, or both, may be required to achieve the desired air content.

Calcium nitrite generally has little effect on the early fresh properties of concrete, as long as proper mixture proportioning has been followed. In a few cases, the acceleratory effect of the material has been found to be associated with slump loss. In this case, the retarded version may be more helpful than adjusting set time with separate retarders, as retardation component is intimately mixed with the calcium nitrite, giving no opportunity for cement to encounter the calcium nitrite in the absence of retarder. Calcium nitrite is an accelerator of both set and strength development of concrete and meets the requirements for accelerators (Type C) in ASTM C494/C494M.

### 13.7—Effects on hardened concrete

The corrosion-inhibiting effect has been discussed previously. Amine carboxylates would have strengths similar to a control and would experience similar amounts of shrinkage as a control. They also will not have any effect on rapid chloride permeability testing (RCPT) of concrete (AASHTO T 277; ASTM C1202).

Depending on the type and proportions of the mixture ingredients, the amine-ester organic inhibitor may also result in a reduction in compressive strength, typically in the range of 5 to 10 percent at the low w/cm used in proportioning concretes exposed to chlorides in service. As a result of its permeability-reducing characteristic, the amine-ester organic inhibitor will reduce the chloride diffusion coefficient and sorption rate of concrete, as indicated by the chloride flux, chloride migration, and sorptivity data summarized in Table 13.7 and the long-term cyclic chloride ponding data shown in Fig. 13.7a.

The data in Fig. 13.7 and additional chloride content data obtained after 2240 days of cyclic ponding in the same evaluation showed that chloride ingress into a 0.50 w/cm concrete treated with the amine-ester organic inhibitor was less than the chloride ingress into the companion 0.40 w/cm concretes. Therefore, the amine-ester organic inhibitor may be more forgiving in situations where a specified w/cm is inadvertently exceeded through the use of additional water in a concrete mixture, or when, for one reason or other, the w/cm of a mixture is greater than code requirements for corrosion protection of steel in concrete. For example, concretes used in balconies of high-rise residential buildings with close proximity to the marine environment would be typical of the latter case. As shown by the corrosion data in Fig. 13.7b, effective corrosion protection of steel in concrete is provided by the amine-ester organic inhibitor through the combined effects of the protective film that it forms and the significant reductions in chloride ingress that it provides.

Calcium nitrite’s corrosion-inhibiting effect has been discussed previously. Aside from this, calcium nitrite also has the effect of increasing the strength of concrete, significantly at early ages, but measurably at 28 days. In some cases, especially with the use of polycarboxylate high-range water reducer, this strength increase can be significant. As

### Table 13.7—Chloride flux, chloride migration, and capillary absorption data for amine-ester organic inhibitor (Buffenbarger et al. 2000)

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Chloride flux,* mm$^2$/year</th>
<th>Chloride migration,† mm$^2$/year</th>
<th>Capillary absorption,* g/m$^2$ s$^1/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference average</td>
<td>39</td>
<td>64</td>
<td>7.6</td>
</tr>
<tr>
<td>Amine-ester organic inhibitor</td>
<td>34</td>
<td>42</td>
<td>3.3</td>
</tr>
</tbody>
</table>

*Average of two specimens.

†Average of three specimens.

Notes: Nominal cement contents of 356 kg/m$^3$; w/cm of 0.45; air entrained. 1 mm$^2$ = 0.002 in.$^2$; 1 g/m$^2$ = 0.03 oz/yd$^2$; 1 kg/m$^3$ = 0.06 lb/ft$^3$.
in all such interactions, the strengths achieved depend on the specific materials used and should be determined by testing. When the RCPT (AASHTO T 277; ASTM C1202) is used to estimate the permeability of concrete, adjustment in the number expected must be made if calcium nitrite is used. The test estimates a concrete’s permeability by essentially measuring its conductivity—the amount of charge passed in coulombs over a certain time. This is a good approximation of how easily chloride will move through the concrete because the charge passed depends on the amount of conducting liquid phase and its interconnectivity in the concrete. The assumption is made in comparing different concretes that the actual conductivities of the liquid phases themselves are similar. However, because calcium nitrite is a salt, and as such increases the conductivity of the liquid phase itself, the rapid chloride number will generally be higher by as much as 30 percent, at equivalent true chloride permeability levels as measured by long-term ponding tests. Accordingly, if design comparisons are being made on an RCPT basis, the best estimate for design purposes of the RCPT of a calcium nitrite concrete is to measure the RCPT for a companion concrete made without the calcium nitrite, but which is otherwise identical.

13.8—Quality assurance and batching

Normal, high-quality control is necessary for concrete containing corrosion-inhibiting admixtures, as it is for all quality concrete. Because the corrosion-inhibiting admixture will provide vital protection necessary for long life of the structure, the need for proper proportioning, batching, and dosing the admixture cannot be overemphasized. All of the items mentioned in 13.6 for the particular corrosion-inhibiting admixture selected should be addressed. They should be batched following the manufacturer’s recommendations.

CHAPTER 14—LITHIUM ADMIXTURES TO REDUCE DELETERIOUS EXPANSION FROM ALKALI-SILICA REACTION

14.1—Introduction

Deleterious expansions from alkali-silica reaction (ASR) can occur in concrete when susceptible siliceous minerals are present in the aggregate. These minerals can begin to dissolve in the highly alkaline pore solution within the concrete, and then react with sodium, potassium, and other ions in solution. These reaction products then combine with water and may produce pressures sufficient to produce deleterious effects in the concrete, such as cracking, popouts, and overall expansion.

The materials-related approach to preventing these deleterious expansions involves four basic approaches, used either alone or in combination. These are: the use of nonreactive aggregates; limiting the alkali content of the concrete mixture; the use of suitable pozzolans in the proper amount; and the use of lithium-bearing admixtures.

14.2—Materials

Currently, there are two solid (powder) forms of lithium admixture and one liquid form of lithium admixture available commercially. The solid forms are lithium hydroxide monohydrate and lithium carbonate, and the liquid form is 30 percent by weight lithium nitrate solution in water. The lithium hydroxide monohydrate is caustic and needs more careful handling than lithium carbonate or the lithium nitrate solution. In addition, an admixture containing lithium nitrite to suppress both alkali-silica reaction (ASR) and corrosion has been patented (Takahara et al. 1990; Stokes and Manissero 2001).

14.3—Mechanism

In the pore solution of the concrete, dissolved silica can combine with sodium (or potassium) ions to form the basis for an alkali-silica gel that can absorb water and expand with deleterious effects on the concrete. If lithium ions are
lithium nitrate also undergoes the early uptake of lithium ion by the hydrating calcium silicate phases, because it does not contribute to any augmentation of the pore fluid hydroxyl ion concentration, this type of effect will not occur with very low dosing of the lithium admixture.

14.4—Dosage

Lithium admixtures are dosed relative to the sodium equivalent of the portland cement content of the concrete mixture. In general, an admixture dose that supplies a 0.74 molar ratio of Li ion to the sodium plus potassium ions supplied by the portland cement is termed the standard, normal, or 100 percent dose (Stokes and Manissero 2001). The amount needed in a given mixture will vary with the alkali loading of the mixture; the aggregate used; and the presence, amounts, and composition of any supplementary cementitious components present in the mixture, but can be referenced as the percent of standard dose. For lithium nitrate admixture (which is supplied as a 30 percent aqueous solution by weight), this is 1.2 gal./oz (4.6 L/kg) of sodium equivalent supplied by the portland cement in the unit volume of concrete. The sodium equivalent of portland cement is calculated as follows:

\[
\text{sodium equivalent} = \frac{\text{wt percent sodium oxide}}{100} + 0.658 \times \frac{\text{wt percent potassium oxide}}{100}
\]

The sodium equivalent for a unit volume of concrete is calculated as follows:

\[
\text{sodium equivalent \ unit volume of concrete} = \frac{\text{lb (kg) portland cement \ sodium equivalent \ unit volume of concrete}}{100}
\]

For lithium hydroxide monohydrate, the standard dose is 1 lb/lb (1 kg/kg) of sodium equivalent supplied by the portland cement in the unit volume of concrete. For lithium carbonate, the standard dose is 0.88 lb/lb (0.88 kg/kg) of sodium equivalent supplied by the portland cement in the unit volume of concrete.

Because of the relatively small volumes of the solid lithium admixtures that may be used in a given concrete mixture, either special equipment is needed to add the material to the mixture, or the material is added manually. The aqueous lithium nitrate admixture is added with conventional admixture dosing equipment.

14.5—Effects on concrete properties

The effects on both hardened and plastic properties of concrete from the use of these admixtures depends on the particular lithium compound used, with lithium hydroxide and lithium carbonate having more pronounced effects in general. These effects are mainly differences in set times. Set times are generally increased with hydroxide. While the carbonate is a very strong accelerator for calcium aluminate cement chemistries, it works as a retarder in portland cement

![Graph showing the expansion of concrete over 2 years with different admixtures](image-url)
systems. Lithium nitrate in general has the least effect on concrete properties (Thomas et al. 2003), and because it has very little potential for adding hydroxide to the pore solution and is more effective at lower dosages, it is generally the preferred form for use in concrete (Folliard et al. 2003). There is generally no particular significant effect with nitrate on any concrete property, hardened or plastic, with the use of lithium nitrate admixture, except a tendency toward acceleration. This effect is neither universal nor strong enough to consider the admixture an accelerator (Thomas et al. 2003). As with all admixtures, however, specific interactions with the vast possibilities of combinations of materials and other admixtures dictates that proper mixture designs be evaluated in a laboratory prior to use in the field.

14.6—Performance tests for effectiveness

There are no standard test methods for evaluating the effectiveness of lithium admixtures in concrete. Most alkali-silica reaction (ASR) mitigation specifications allowing lithium admixtures are based either on a prescriptive specification, such as the standard dose, or describe modifications to either ASTM C1293 or ASTM C1260 (Folliard et al. 2003). In the case of ASTM C1293, the normal modification employed is to add the lithium admixture to the mixture and note the percent expansion at 2 years (Folliard et al. 2003). Modifications involving ASTM C1260 generally involve adding the admixture to both the mortar and to the soak solution (Folliard et al. 2003). The actual expansion limits used to evaluate these results varies with the specifying agency. These may range from as high as 0.1 percent at 14 days to as low as 0.08 percent at 28 days in modifications to the accelerated mortar bar tests (ASTM C1260; ASTM C1567). For testing in ASTM C1293, the limit is generally less than 0.04 percent at 2 years.

In Fig. 14.3, the LiOH and LiNO\(_3\) were both added at the 100 percent dose; note the greater effectiveness of the LiNO\(_3\). As a demonstration of the high reactivity level of this aggregate, note that levels of Class F fly ash (ACI 232.2R) up to 30 percent were not sufficient to control the expansion of this aggregate. Often, 30 percent of Class F fly ash will suppress expansion of most aggregates used for concrete manufacture in North America. Note that the 100 percent dose of LiNO\(_3\) will not always be sufficient for every aggregate. Performance testing is recommended when using Li-based admixtures.

14.6—Quality assurance and batching

Normal, high quality control is necessary for concrete containing alkali-silica reaction (ASR) admixtures, as it is for all quality concrete. Because the ASR admixture will provide protection necessary for long life of the structure, the need for proper proportioning, batching, and dosing the admixture cannot be overemphasized. ASR admixtures should be batched following the manufacturer’s recommendations.

CHAPTER 15—PERMEABILITY-REDUCING ADMIXTURES

15.1—Introduction

While it is generally accepted that well-proportioned and properly cured concrete produced using a low w/cm will result in a finished product with good durability and low permeability, no concrete structure is absolutely waterproof (Perkins 1986). Concrete is a porous material, and water can penetrate concrete through pores and microcracks due to capillary absorption, often referred to as wicking, or due to hydrostatic pressure. Capillary absorption is the movement of water through the small pores in concrete in the absence of an externally applied hydraulic head, and is the result of surface tension between the water and the pore wall. The permeability of concrete is the movement of water due to a pressure gradient, such as water in contact with a concrete structure installed underground. In some cases, porosity may be exacerbated by external factors such as incomplete consolidation and curing, which may ultimately lead to leakage and reduced durability. The addition of supplementary cementing materials (SCMs) into concrete mixtures has been gaining acceptance for improving durability and reducing permeability (Munn et al. 2005). In addition, a class of materials referred to as permeability-reducing admixtures (PRAs) have been developed to improve concrete durability through controlling water and moisture movement (Roy and Northwood 1999), as well as by reducing chloride ion ingress (Aldred 1988; Munn et al. 2003) and permeability (Munn et al. 2005). PRAs encompass a range of materials with variances in performance.

Although PRAs are traditionally subcategorized as dampproofing and waterproofing admixtures (Ramachandran 1995; Aldred 1989), perhaps it is too absolute to state that concrete can be made waterproof. Further complicating matters, many concrete professionals use the term “permeability” to define the resistance of concrete to water ingress under actual service conditions. This definition is not technically correct, as it could refer to either permeability or capillary absorption as defined previously; however, permeability is commonly understood to refer to any passage of water through concrete. For the purpose of this chapter, admixtures intended to reduce water ingress will be split into two subcategories: PRAs for concrete exposed to nonhydrostatic conditions (PRAN) and PRAs for concrete exposed to hydrostatic conditions (PRAH). In addition to permeability reduction, some PRAs may exhibit other beneficial characteristics such as reduced drying shrinkage (Munn et al. 2003), lowered chloride ion penetration (Aldred 1988; Munn et al. 2003), enhanced freezing-and-thawing resistance (Ramachandran 1995; Rixom and Mailvaganam 1999), and enhanced autogenous sealing (Skoglund and Johansson 2003; Kubal 2000).

Users of a PRA should evaluate performance of the product in concrete based on the application requirements. A commercial PRA can include components from several material categories (15.2), making classification as a PRAN or PRAH based strictly on terminology or chemistry inaccurate. The final selection should be based on the project
requirements and the performance of the PRA based on appropriate testing, as described in 15.3. The PRA manufacturer is responsible for conducting tests to demonstrate the PRA is suitable for its recommended application. The PRA’s performance should be evaluated over a sufficient amount of time to demonstrate the long-term performance of the product, as some PRAs have an extended history of successful use (Neville 1995; Aldred 1988, 1989; Ropert and Robertson 2012).

15.2—Materials
Permeability-reducing admixtures (PRAs) typically include, but are not limited to, the following categories:

a) Hydrophobic water repellants
b) Polymer products
c) Finely divided solids
d) Hydrophobic pore blockers
e) Crystalline products

These materials are used alone or in combination to give varying ranges of performance.

15.2.1 Hydrophobic water repellants—Hydrophobic water repellents include materials based on soaps and long-chain fatty acid derivatives; vegetable oils such as tallows, soya-based materials, and greases; and petroleum such as mineral oil and paraffin waxes. Perhaps the most widely used hydrophobic materials are based on salts of fatty acids. Calcium, ammonium, and butyl stearates are also commonly used materials, as well as oleic, caprylic, and capric derivatives (Ramachandran 1995; Rixom and Mailvaganam 1999).

According to Ramachandran (1995), these materials react according to the following reaction

$$\text{Ca(OH)}_2 + \text{RCOOH} \rightarrow \text{Ca}^+\text{COOR}^- + \text{H}_2\text{O}$$

(calcium hydroxide (lime) + stearate admixture → insoluble calcium stearate + water)

The insoluble stearate created by the reaction between the admixture and the lime forms a hydrophobic layer on the walls of the concrete pores. Waxes and oils are other materials that can impart a hydrophobic effect, although there is no chemical reaction involved in that process. Hydrophobic admixtures are effective at reducing the capillary absorption of concrete and chloride ingress of concrete under nonhydrostatic conditions (Ramachandran 1995; Rixom and Mailvaganam 1999).

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Fig. 15.2.1a—Water absorption for ordinary portland cement (OPC) concrete with hydrophobic ingredient (HI) (BS 1881-122) with an age of 28 days and a w/cm of 0.40.

Fig. 15.2.1b—Chloride penetration of a hydrophobic permeability-reducing admixture (PRA) subjected to ponding. Tested using modified chloride ponding protocol (not the AASHTO T 259 procedure discussed in 15.3). Cementitious content is 690 lb/yd² and w/cm is 0.40. (Note: 1 in. = 25.4 mm; 1 lb/yd² = 0.5933 kg/m².)

The insoluble stearate created by the reaction between the admixture and the lime forms a hydrophobic layer on the walls of the concrete pores. Waxes and oils are other materials that can impart a hydrophobic effect, although there is no chemical reaction involved in that process. Hydrophobic admixtures are effective at reducing the capillary absorption of concrete and chloride ingress of concrete under nonhydrostatic conditions, as shown in Fig. 15.2.1a and 15.2.1b, respectively (Aldred et al. 2001; Civjan and Crellin 2008).

In theory, the hydrophobic layer should be able to resist water up to 13.12 ft (4 m) head pressure (Ramachandran 1995) and even up to 45.92 ft (14 m) (Aldred et al. 2001), but after accounting for the fact that the material is unlikely to completely and uniformly coat all pores, plus the presence of larger voids, the hydrophobic layer can usually only resist a few centimeters of head pressure (Ramachandran 1995). For this reason, these materials are generally used in conditions in which there is little or no hydrostatic pressure.

15.2.2 Polymer products—Some polymer materials include organic hydrocarbons supplied either as emulsions (latex), or in liquid form, and may include coal tar pitches, bitumen or other resinous polymer, or prepolymer materials. Some polymer materials coalesce within the concrete mass to form water-repellent films. Others have been reported to form globules that plug capillaries once hydrostatic pressure has been applied. Some of these materials have been found to resist hydrostatic pressure (Ramachandran 1995). One use of polymer-latex admixtures has been to reduce permeability of concrete overlays for bridge decks and parking decks.

15.2.3 Finely divided solids—Finely divided solids include materials such as inert and chemically active fillers such as talc, bentonite, silicious powders, clay, lime, silicates, and colloidal silica. Finely-divided solids may resist water ingress by increasing density or by simply filling voids. The denser concrete has reduced porosity, which restricts the movement of water; however, the degree of pore blocking will depend on the properties of the finely divided solid material. Finely divided solids may be used in combination with hydrophobic water-repellent chemicals for a synergistic effect (Fig. 15.2.3a) (British Board of Agrément 2000).

Supplementary cementing materials (SCMs) such as fly ash, raw or calcined natural pozzolans, silica fume (ACI 232.1R; ACI 232.2R; ACI 234R), or slag cement (ACI 233R), although not chemical admixtures, can contribute to reducing
Concrete permeability and be a complementary component in a well-proportioned mixture incorporating PRAs. Figures 15.2.3b and 15.2.3c demonstrate the permeability under pressure of concrete mixtures containing fly ash and similar mixtures containing a crystalline PRA (15.2.5) at 10 months. The crystalline admixture resulted in a significant reduction in permeability when added to the fly ash mixture (Steward and Morgan 1994; Aloysius and Steward 1995).

**15.2.4 Hydrophobic pore blockers**—Hydrophobic pore blockers (HPBs) can be single components or combinations of the materials listed in 15.2. Some hydrophobic pore blocking admixtures report to have two distinct actions. The first is a reaction of the hydrophobic compounds with hydrating cement phases, modifying the cement paste matrix and changing the surface tension of the capillary surfaces, reducing the capillary movement of water through the concrete mass. The second action—a component of the HPB is reported to collect in the capillaries forming a physical plug, blocking the capillary system and preventing further water entry (Ramachandran 1995; Aldred 1988). HPBs containing prepolymers report to reduce permeability by polymerizing in concrete.

Some HPBs have been reported to resist water penetration against hydrostatic pressure (Fig. 15.2.4) (British Board of Agrément 2006). Concrete treated with some HPBs demonstrated improved corrosion resistance compared to a reference concrete (Goodwin et al. 2000; Civjan et al. 2003; Civjan and Crellin 2008; Dao et al. 2010).

**15.2.5 Crystalline products**—Crystalline materials consist of proprietary active chemicals provided in a carrier of cement and sand. The hydrophilic nature of these materials causes them to increase the density of calcium silicate hydrate (CSH), generate pore-blocking deposits, or both, that resist water penetration. Crystalline admixtures are hydrophilic, and the active ingredients react with water and cement particles in the concrete to form CSHs, pore-blocking precipitates, or both, in the existing microcracks and capillaries. The mechanism is analogous to the formation of CSHs and the resulting crystalline deposits become integrally bound.
with the hydrated cement paste. The resulting concrete could have significantly increased resistance to water penetration under pressure. An overview of the general process is represented by the following:

$$3\text{CaO-SiO}_2 + \text{M}_x\text{R}_y + \text{H}_2\text{O}\text{Ca}_3\text{Si}_2\text{O}_7\text{R}-(\text{H}_2\text{O})_x + \text{M}_x\text{CaR}_y-(\text{H}_2\text{O})_x$$

(calcium silicate + crystalline promoter + water-modified calcium silicate hydrate + pore-blocking precipitate)

Similar reactions may exist involving calcium aluminates, but the aforementioned process is expected to predominate due to the abundance of calcium silicates.

These crystalline deposits develop throughout the depth of the concrete and become a permanent part of the concrete mass. Some crystalline materials have been reported to resist water penetration against hydrostatic pressure (Fig 15.2.5) (British Board of Agrément 2005). As hairline cracks form over the life of concrete, some crystalline admixtures continue to active in the presence of moisture and seal additional gaps (Kubal 2000; Skoglund and Johansson 2003; Biparva et al. 2011). Reports indicate that once fully cured, crystalline admixtures can withstand hydrostatic pressures of 400 ft (122 m) of head (Kubal 2000). Concrete treated with a crystalline material demonstrated improved corrosion resistance compared to a reference concrete after 10 years of exposure in a marine environment (Ropert and Robertson 2012).

15.3—Selection and evaluation

The selection of a permeability-reducing admixture (PRA) depends largely on the service conditions. Nonhydrostatic service conditions can be defined as those exposed to little or no water under hydrostatic head pressure, primarily when the main mechanism of water movement is capillary absorption. In these situations, PRAs for concrete exposed to nonhydrostatic conditions (PRANs) are often sufficient. On the contrary, under hydrostatic conditions, moisture is transported into concrete under pressure. Whereas PRANs are unable to effectively block the movement of water under hydrostatic head pressure (Ramachandran 1995) experienced in below-grade structures and water-retaining structures, PRAs for concrete exposed to hydrostatic conditions (PRAHs) are well suited to these applications. PRAHs are also suited to withstand ponded water (Palmer 2004). To resist hydrostatic pressure, PRAHs employ a pore-blocking mechanism, although the ability to withstand hydrostatic pressure will depend on how completely the pores are blocked and the stability of the deposits under pressure. The PRAH should be selected based on the admixture’s demonstrated ability to reduce water penetration under the expected service conditions. If the PRAH forms part of a primary waterproofing system, consider crack control measures (control joints), the admixture’s crack sealing abilities, treatment of construction joints, and compatible repair systems. Also consider using concrete with the lowest drying shrinkage possible. Leaking cracks are often addressed separately using suitable repair methods. The admixture supplier should be consulted regarding the recommended method of crack repair. Emphasize that a PRAN should not be used to resist hydrostatic pressure.

In addition to service conditions and level of performance, other factors will also contribute to the selection of a PRA. Some materials may affect the plastic properties of concrete, such as air entrainment, setting time, and water reduction. Also, depending on the manufacturer, PRAs are available in either liquid or solid form. Form will affect the method of addition. The basis for achieving low-permeability concrete and optimizing the performance of PRAs and other admixtures is to address factors affecting the quality of the mixture, including proper proportioning and w/cm, quality of raw materials, and inclusion of supplementary cementing materials (SCMs) and other admixtures. Recommendations from manufacturers of each PRA can guide the user to the correct dosage rate and directions for use.

The effects of admixtures can be evaluated by testing the permeability of concrete through direct and indirect methods. When evaluating a PRA for use against direct water pressure (PRAH), a direct measurement using hydrostatic pressure should be used, as this most closely simulates the service conditions found in water tanks, basements, and similar applications. The U.S. Army Corps of Engineers (1992) test method is a direct measurement of concrete permeability resistance during exposure to water under 200 psi (1.28 MPa) of hydrostatic pressure. After a steady state of flow has been established, Darcy’s equation can be used to calculate the coefficient of permeability, $K$. European tests, such as DIN 1048-5 and BS EN 12390-8, measure the penetration of water under hydrostatic pressure into a concrete specimen. The European standards instruct users to expose the concrete to 72.5 psi (0.5 MPa) of water for 72 hours. The specimens are then split in half and the depth of water penetration is measured. Some testing agencies use a similar procedure, but expose the concrete to 150 psi (1.0 MPa) for 96 hours,
and then use Valenta’s equation to calculate the coefficient of permeability based on penetration depth (Taywood/Valenta method) (Valenta 1969). The use of Valenta’s equation requires the increase in mass for each specimen to be accurately measured to determine the fraction volume of discrete pores in the concrete (Neville 1995), which is not part of BS EN 12390-8.

Many factors can affect the water-resisting properties of concrete. In particular, the cement content, w/c, and inclusion of SCMs can significantly affect the permeability and absorption. While these factors are relevant to the concrete’s final performance, they can sometimes give misleading results when evaluating PRAs. For example, in some cases, a PRA may be supplied as multi-component systems that incorporate high-range water-reducing admixtures (HRWRAs) in addition to hydrophobic or pore-blocking ingredients. Therefore, the reported reduction in permeability may be partly due to significantly reduced water contents from the HRWRA, if the w/cem is lowered. To properly evaluate a PRA, it is important to hold these key factors (cement type and content and w/c) constant wherever possible, and to consider what affect any variations in these properties may have had on the final test results. When tested at equal cement and water contents with a w/cem of 0.45 or less, PRAHs can result in a significant reduction in water penetration under pressure compared to a reference concrete. Reductions in the depth of water penetration of 50 to 90 percent have been reported using penetration methods such as BS EN 12390-8 or DIN 1048-5 (Aloysius and Steward 1995; Morelly 2003).

One widely-used indirect method for inferring permeability information is ASTM C1202. This method measures the current that passes through a concrete specimen exposed to electrolyte solutions and an electric potential. This test method is commonly referred to as the rapid chloride permeability test (RCPT). This description, however, is technically inaccurate because the test procedure measures the charge passed through a concrete sample and not the concrete permeability. While widely recognized, this test method cannot distinguish between the charge passed due to the presence of chlorides compared with other ions in the pore solution. Results can vary when different chemistries are introduced into the mixture, causing misleading results (Obla and Lobo 2007).

Alternate electrical migration techniques have been proposed, including the rapid migration test that measures chloride penetration by splitting the specimens open and applying a silver nitrate indicator (Stanish et al. 1997). Standardized procedures, however, have not been published. The use of electric potential to facilitate chloride penetration does not necessarily replicate the transport of chloride ions in real-life situations (Neville 1995). It does, however, get quick results. Resistance to chloride-ion penetration can also be determined by ponding a chloride solution on a concrete surface and, after 90 days, determining the chloride content of the concrete at particular depths (AASHTO T 259; AASHTO T 260). The results from this test can be used to compute an apparent diffusion coefficient using ASTM C1556. Various absorption methods are used to evaluate PRAs as well, including ASTM C1585 and BS 1881-122. Absorption or sorptivity tests generally report the mass of water uptake after a certain time interval, or rate of water uptake over a given time period to determine the rate of water penetration. Absorption tests do not apply hydrostatic pressure and are, therefore, most suitable for testing PRANs. The length of testing should be considered. Longer-term absorption tests, such as ASTM C642, indicate total porosity but not the rate of penetration. Some results may only report absorption for a short time periods (for example, up to 60 minutes), which would make such results most applicable to applications with intermittent and short-term water exposure. Absorption tests alone are not recommended for evaluating admixtures for PRAH applications because of the lack of hydrostatic water pressure. The choice of test depends on whether the concrete should withstand exposure to water under hydrostatic pressure, and whether a direct measurement is required.

15.4—Applications

The user of a permeability-reducing admixture (PRA) should evaluate the performance of a product in concrete based on the requirements of the application. PRAs can be incorporated into virtually any concrete mixture. Their use, however, is usually limited to structures that will be exposed to moisture, salt, salt water, wicking, or water under hydrostatic pressure. Prevention of water-related problems such as water migration, leaking, freezing-and-thawing damage, corrosion, and efflorescence are reasons to choose a PRA. PRAs for concrete exposed to hydrostatic conditions (PRAHs) are appropriate for water-containment structures, below-grade structures, tunnels and subways, bridges and dams, and recreational facilities such as aquatic centers. These materials in a properly proportioned mixture with a w/cem of 0.45 or less can generally withstand aggressive environments with exposure to salt spray and some chemicals.

PRAs for concrete exposed to nonhydrostatic conditions (PRANs) are used normally for repelling rain and minimizing dampness. These admixtures can improve the quality of concrete pavers, tiles, bricks, blocks, exposed concrete facades and cladding panels where the additional benefits of reduced efflorescence, and the maintenance of clean surfaces and more even drying of adjacent bricks and panels, are desired. PRANs may reduce the penetration of water into concrete, delaying the effects of damage caused by freezing and thawing and reducing the amount or rate of moisture entering the concrete.

15.5—Dosage and proportioning concrete

Permeability-reducing admixtures (PRAs) are intended to be used in, and complement, well-proportioned concrete mixtures, not to compensate for poorly proportioned concrete mixtures. Although recommendations differ from each manufacturer, a w/cem of 0.45 or less is typical for concrete designed to resist water movement. Proportioning recommendations for various PRAs will differ based on parameters such as chemical reactivity, and if the admixture is in solid or liquid form. The PRAs are generally added at
a prescribed percentage by weight of cement or cementitious content. Admixture manufacturers can provide more detailed guidelines for their type of PRA.

15.6—Effects on fresh and hardened properties

Permeability-reducing admixtures (PRAs) are usually added into concrete for the sole purpose of reducing the passage of water. These admixtures, however, can have a range of secondary effects in the plastic and hardened concrete. Some PRAs will act as low-range water reducers, entrain air, or affect the setting time of concrete. In the plastic state, these materials can affect finishing properties, consistency, and scheduling. In the hardened state, changes to compressive strength, freezing-and-thawing resistance, and shrinkage often result. Trial batches are recommended to ensure that the plastic and hardened properties of the concrete meet expectations.

15.7—Quality assurance and batching

Determining that an admixture is similar to that previously tested or that successive lots or shipments are similar is desirable and sometimes necessary. Tests that can be used to identify admixtures include solids content, density, infrared spectrophotometry for organic materials, chloride content, and pH. The uniformity requirements in ASTM C494/C494M are a useful guide; however, ASTM C494/C494M does not specifically cover PRAs. Admixture manufacturers can recommend which tests are most suitable for their admixtures and the results to expect.

15.7.1 Field control at job site—Field control testing can vary depending on the type of admixture used and the manufacturer’s recommendations. Trial batches are necessary to help optimize the mixture design and ensure the mixture meets the specifications. In addition, an on-site placement to verify proper workability, finishability, and setting time is beneficial. On-site quality control testing should include water content, slump, air content, and concrete temperatures. Cylinders are usually cast for compressive strength testing, and additional samples may be cast for permeability testing. If permeability samples are prepared, it is useful to obtain a reference concrete either by taking a sample before the PRA is added or performing trial batches. Water-resisting performance should be measured on the approved trial mixture using suitable procedures depending on the application and as advised by the PRA supplier. Examples are absorption, permeability, and coulomb. Should the need arise for future troubleshooting or for purposes of analyzing historical trends, accurate record-keeping is essential. Be sure to record information about plastic properties, lot numbers, dosage rates, dates, and environmental conditions.

15.7.2 Batching—Batching recommendations for various PRAs will differ based on parameters such as chemical reactivity and whether the admixture is a solid or a liquid. Admixture manufacturers can provide guidelines for their type of PRA, stipulating the addition rate, order of addition, mixing time, and compatibility with other materials.

CHAPTER 16—MISCELLANEOUS ADMIXTURES

16.1—Bonding admixtures

16.1.1 Materials—Admixtures formulated to enhance bonding properties of hydraulic-cement-based mixtures generally consist of an organic polymer dispersed in water (latex) (Goek 1958; Ohama 1984). In general, the latex forms a film throughout the mixture. Polymer latex for use as a concrete admixture is formulated to be compatible with the alkaline nature of the portland cement paste and the various ions present. Unstable latex will coagulate in the mixture, rendering it unsuitable for use. When used in the quantities normally recommended by manufacturers, which is 5 to 20 percent of polymer solids by mass of cement, different polymers can affect the unhardened mixture differently. For example, a film-forming latex can cause skinning upon contact with air. Concrete and mortar modified with polymers are more fully addressed in ACI 548.3R.

16.1.2 Curing—Water is still necessary to hydrate the portland cement of the cement-polymer system. The polymer latex carries a portion of the mixing water into the mixture; the water is released to the cement during the hydration process. Removing water causes the latex emulsion to coalesce, forming a polymer film. Therefore, after an initial 24 hours of moist curing to reduce plastic-shrinkage cracking, additional moist curing is unnecessary and is actually undesirable because the latex film needs an opportunity to dry and develop the desired properties. The polymer improves the bond between the various phases and also fills microvoids and bridges microcracks that develop during the shrinkage associated with curing (ASTM C881/C881M; Isenburg 1971; Whiting 1981; Shen et al. 2007; Wu and Huang 2008). This secondary bonding action preserves some of the potential strength normally lost due to microcracking.

16.1.3 Effect on concrete properties—Greater tensile strength and durability are associated with latex mixtures. The surfactants used in producing latex act as water-reducing admixtures, resulting in more fluidity than in mixtures without latex, but with a similar w/cm. The compressive strength of moist-cured grouts, mortars, and concrete made with these materials is often less than that of mixtures with the same cementitious material content without the admixture, depending on the admixture used. The increases in bond, tensile, and flexural strengths, however, can outweigh the disadvantage of a compressive-strength reduction. Polymer-modified concrete has better abrasion resistance, better resistance to freezing and thawing, and reduced permeability compared with similar concrete not containing the polymer.

16.1.4 Limitations—Surfactants present in latex can entrain air and require that a foam-suppressing agent, or defoamer, be used. Air-entraining agents are not recommended for use with polymer-modified concrete. Some polymers, such as vinyl acetate homopolymer, decompose (hydrolyze) and soften in the presence of water; they should not be used in concrete that will become moist during service. The result obtained with a bonding admixture is only as good as the surface to which the mixture is applied. The surface should
be clean, sound, and free from such foreign matter as paint, grease, and dust.

16.2—Coloring admixtures

16.2.1 Materials—Coloring admixtures specifically prepared for use in concrete and mortar are available both as natural or synthetic materials, and in liquid or dry forms (Ball and DeCandia 2002). They produce adequate color without affecting the desirable physical properties of the mixture. Coloring admixtures are often multi-component materials that contain pigments that are in compliance with ASTM C979/C979M. The pigments listed in Table 16.2.1 may be used to obtain a variety of colors.

The addition rate of any pigment to concrete normally should not exceed 10 percent by mass of the cementitious material (Wilson 1927; ASTM C979/C979M); however, some fine pigments, such as carbon black, should be used at much lower addition rates. Natural pigments are usually not as finely ground nor as pure as synthetic materials and, consequently, do not produce as intense a color. Brilliant concrete colors are not possible with either natural or synthetic pigments due to their low allowable addition rates and the masking effects of the cement and aggregates. Cleaner colors can be obtained if white rather than gray cement is used. Liquid coloring admixtures are generally dispensed using automated equipment, providing increased accuracy in dosing and cleaner operations.

16.2.2 Effects on concrete properties—Except for carbon black, adding less than 6 percent of pigment has little or no effect on the physical properties of the fresh or hardened concrete. Larger quantities can increase the water requirement of the mixture to such an extent that the strength and other properties, such as abrasion resistance, are adversely affected. Adding unmodified carbon black considerably increases the amount of air-entraining admixture needed to provide resistance of the concrete to freezing and thawing (Taylor 1948; Ball and DeCandia 2002). Some carbon blacks available for coloring concrete may contain surfactants in sufficient quantity to offset the air-entraining, inhibiting effect of the carbon black.

16.3—Flocculating admixtures

Synthetic polyelectrolytes, such as vinyl acetate-maleic anhydride copolymer, have been used as flocculating admixtures. Published reports (Bruere and McGowan 1958; Vivian 1962) indicate that these materials increase the bleeding rate, decrease the bleeding capacity, reduce flow, increase cohesiveness, and increase early strength. Although the mechanism of this action is not fully understood, it is believed that these compounds, containing highly charged groups in their chains, are absorbed on cement particles, linking them together. The net result is equivalent to an increase in interparticle attraction, which increases the tendency of the paste to behave as one large flock. Bruere and McGowan (1958) discuss uses for these admixtures, including use as an alternative to importing fine sand to correct deficiencies in sand gradings, reducing bleeding and segregation, and improving green strength of molded products.

Table 16.2.1—Pigments used to produce various colors

<table>
<thead>
<tr>
<th>Color</th>
<th>Pigment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray to black</td>
<td>Black iron oxide</td>
</tr>
<tr>
<td></td>
<td>Carbon black (indoors)</td>
</tr>
<tr>
<td>Blue</td>
<td>Phthalocyanine blue (indoors)</td>
</tr>
<tr>
<td></td>
<td>Cobalt blue</td>
</tr>
<tr>
<td>Red</td>
<td>Red iron oxide</td>
</tr>
<tr>
<td></td>
<td>Brown iron oxide</td>
</tr>
<tr>
<td>Brown</td>
<td>Raw burnt umber</td>
</tr>
<tr>
<td></td>
<td>Chromium oxide</td>
</tr>
<tr>
<td>Green</td>
<td>Phthalocyanine green</td>
</tr>
<tr>
<td>Yellow</td>
<td>Yellow iron oxide</td>
</tr>
<tr>
<td>Ivory, cream,</td>
<td>Yellow iron oxide (with white cement)</td>
</tr>
<tr>
<td>or buff</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>Titanium dioxide (with white cement)</td>
</tr>
</tbody>
</table>

16.4—Fungicidal, germicidal, and insecticidal admixtures

Certain materials have been suggested as admixtures for concrete or mortar to impart fungicidal, germicidal, and insecticidal properties. The primary purpose of these admixtures is to inhibit and control the growth of bacteria and fungi on concrete floors and walls or joints. The materials that have been found to be most effective are polyhalogenated phenols (Leovitz 1952), dieldrin emulsion (Gay and Wetherly 1959), and copper compounds (Robinson and Austin 1951; Young and Talbot 1945). Addition rates vary from 0.1 to 10 percent by mass of the cement, depending on the concentration and composition of the chemical. Addition rates above 3 percent may reduce the strength of the concrete. The effectiveness of these materials, particularly copper compounds, is reportedly temporary and probably varies with the type of exposure and cleaning methods used.

16.5—Air-detraining admixtures

16.5.1 Introduction—Air-detraining admixtures, sometimes referred to as defoamers or deaerators, are used to reduce the air content in a variety of applications including, but not limited to, well cementing, cement slurries, and concrete mixtures.

16.5.2 Materials—The most widely used air-detraining chemicals are 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. Air-detraining admixtures lower surface tension and should be insoluble in water to be effective.

16.5.3 Effect—High air contents can be caused by inadvertently overdosing the air-entraining agent or by using other admixtures that have a tendency to entrain air. Some aggregates or contaminants can increase the total air content of concrete. Air-detraining admixtures are added in small amounts—approximately 0.2 percent by weight of cement is a starting point. Air-detraining admixtures do not normally remove all entrained air so they should be used judiciously for the concrete to end with the correct air amount. While these admixtures are appropriate for interior floors, they
should only be used in air-entrained exterior work if prior testing has shown resulting air to be of required quality.

16.6—Expansive/gas forming admixtures

16.6.1 Introduction—This section discusses the use of materials producing expansion in the plastic state only by liberating gas into the matrix. Those producing expansion in the hardened state are discussed in Chapter 12.

16.6.2 Materials—The most common components of these admixture types are metallic aluminum, zinc or magnesium, hydrogen peroxide, nitrogen and ammonium compounds, and certain forms of activated carbon or fluidized coke.

16.6.3 Applications—This type of admixture generates gas bubbles in the fresh mixture during hydration process, before the initial set takes place. They are used to control settlement and bleeding and improve the intrusion of grout and mortars by producing an expansion of 5 to 10 percent. They are also in products used for placement in confined areas under base plates, for example.

16.6.4 Effects on concrete properties—After addition of an expansive admixture, a reaction occurs between the admixture and components of the fresh hydraulic cement mixtures. When a known amount of gas-forming admixture is added, a known volume of gas, a predetermine rate of expansion, and its duration is expected; these are important factors to control for the quality and performance of grout or mortar. Proper distribution and bubble size generated by the reaction are important as well.

Hydrogen, oxygen, nitrogen, or air is released by chemical reaction. Aluminum powder reacts with the calcium hydroxide liberated by the cement hydration to form hydrogen. Aluminum powder used as expansive agent for cable grouting has been linked to failure of some tendons due to steel embrittlement and, therefore, is prohibited by certain agencies. Hydrogen embrittlement is the process by which various metals—most importantly, high-strength steel—become brittle and fracture following exposure to hydrogen.

Hydrogen peroxide and calcium hypochlorite will form oxygen and release calcium chloride. Consider acceleration of the time-of-set and potential corrosion. Nitrogen gas is produced by decomposition of the N-N bond of the compound used. Activated carbon and fluidized coke will liberate adsorbed air.

The mixture proportion, cement characteristics, and temperature and type of admixture used will influence the gas evolution, making it essential to understand how to dose them properly for the specific application and expansion desired.

16.7—Admixtures for cellular concrete/flowable fill

16.7.1 Introduction—Cellular concrete is generally produced with the use of an admixture termed as a “foaming agent.” The major method of production is a two-stage process. In the first stage, a foam generator is used to generate a highly stable foam. Normally, 1 to 2 percent solution of the foaming agent is passed through the foam generator for sufficient time to generate a dense foam. In the second stage, a blender, which is typically ribbon type, is used to blend cement and water or cement and fine aggregate and water slurry with the pregenerated foam. Dry densities between 420 to 2700 lb per cubic yard (250 to 1600 kg per cubic meter) are possible. Typical dry densities are in the range of 675 to 1350 lb per cubic yard (400 to 800 kg per cubic meter).

Ready-to-use admixtures added directly into the concrete are also used to produce air contents of up to 35 percent in various flowable fill applications where reduced densities, or unit weights, are desired. For delivery efficiencies, these admixtures can be added at the job site.

16.7.2 Materials—Two types of foaming agents are available, depending on the source. One type is based on protein and the other on synthetic surfactants. ASTM C869/C869M is the specification for foaming agents and the test method is given by ASTM C796/C796M. Admixtures for flowable fill applications are typically surfactants (Nmaei et al. 1997).

16.7.3 Applications—Main uses of cellular concrete/flowable fill include flat roof insulation screed; fire protection of timber floors and structural steel works; soil replacement for backfilling and ground stabilization; fabrication of lightweight beams, blocks, and panels; filling of old underground pipes, tunnels, sewers, storage tanks, shelters and basements; trench reinstatement; and acoustic insulation (ACI 229R).

16.7.4 Effects on concrete properties—At normal dosages, the main effect will be entrapment/entrainment of air in the concrete or mortar mixture. This helps reduce the mixture density to desired value. At higher-than-recommended dosages, it could adversely affect the final setting time of the mixture and reduce the density, as well as compressive strength, to undesired levels. Due to entrapped air, the thermal conductivity decreases in proportion to the dry density.

The most important performance parameters of admixtures for cellular concrete and flowable fill are:

a) Good stability to highly alkaline conditions
b) Good temperature stability, so that the performance does not alter much during summer and winter
c) Least effect on concrete setting times
d) Develop good rheology that is suitable for pumping
e) No collapse or reduction of foam after casting, which may lead to cracks, debonding, and reduction in actual thickness of the pour

16.8—Shotcrete admixtures

16.8.1 Introduction—The main types of chemical admixtures used for shotcrete application are shotcrete accelerators, extended set-control admixtures (ESCA) and high-range water-reducing admixtures (HRWRAs). Sometimes other admixtures, such as an air-entraining admixture, viscosity modifying admixtures (VMAs), pumping aids, waterproofing admixtures, and others are also used. This section will focus mainly on shotcrete accelerators and ESCA and HRWRAs from a shotcrete view point.

16.8.2 Shotcrete—As per ACI 506R, shotcrete is defined as “mortar or concrete pneumatically projected at high velocity onto a surface.” Some of the main advantages of shotcrete over conventional cast-in-place concrete are concreting without formwork, concrete with early load-bearing capacity, faster construction, safe and rapid access to work area, concreting in confined spaces, good adhesion,
concreting on uneven substrates, uneven thickness, and thin layers and flexibility during construction. Some of the most common applications of shotcrete are excavation stabilization—for example, tunnels and mines—and slope or rock stabilization; repair, rehabilitation, and waterproofing; and architectural concrete.

There are two types of shotcrete processes: dry-mix and wet-mix. In the dry-mix process, all concrete or mortar ingredients except water are mixed thoroughly and fed in the delivery equipment where it is carried by compressed air to the nozzle. The water then gets added at the nozzle before the material is sprayed on the substrate. In the wet-mix process, all the concrete or mortar ingredients are mixed thoroughly and fed in the delivery equipment and transported to the nozzle by positive displacement or compressed air. If a shotcrete accelerator is used, it gets added to the wet concrete at a controlled rate at the nozzle before the concrete is sprayed (ACI 506R).

16.8.3 Shotcrete accelerators—Shotcrete accelerators are admixtures that are added to sprayed concrete at the nozzle of the concrete spraying equipment during the wet or dry shotcrete process. Shotcrete accelerators in liquid form are used mostly for shotcrete. In the case of dry shotcrete, the accelerator could be a powder, which may be preblended with the dry mix during manufacturing.

16.8.3.1 Effect—in wet shotcrete, depending on the pumping distance, concrete is pumped at moderate to high workability. Without shotcrete accelerators it is difficult to place shotcrete, as the concrete will not adhere to the substrate and will rebound and prevent higher buildup. When a shotcrete accelerator is added to concrete, it quickly reacts with the cement (tricalcium aluminate component) and causes early stiffening of the cement paste. This enables better bonding of the concrete to the substrate, increasing buildup and, in some cases, reducing rebound. Shotcrete accelerators decrease the set time and increase the early-age strength of concrete. The effect of different shotcrete accelerators can vary widely. Factors that can affect the performance of shotcrete accelerators are materials, mixture proportions, temperature conditions, and shotcrete application technique.

16.8.3.2 Materials—Shotcrete accelerators are classified into alkali-based shotcrete accelerators and alkali-free shotcrete accelerators. Alkali-based accelerators are based on aqueous silicate or aluminate solutions; they usually exhibit a high pH (above 11). Alkali-free accelerators are based on aluminum sulfates and aluminum hydroxisulfates. The pH of alkali-free accelerators is low—in the range of weak acids (approximately 3.0).

Alkali-based shotcrete accelerators, due to high pH, are caustic and can affect human health, including damage to the skin, eyes, and lungs from their presence in the air or direct contact. Also, performance-wise, alkali-based accelerators tend to reduce the later-age strength of shotcrete (typically 20 to 30 percent). For these reasons, alkali-free products are most commonly used in shotcrete application.

16.8.4 High-range water-reducing admixtures—As compared with conventional concrete, shotcrete mixes have a lower w/cm to reduce rebound, enhance adhesion to substrate, and develop high early strength. Oftentimes, shotcrete mixes also contain silica fume (ACI 234R), which has a high water demand. In shotcrete, as in conventional concrete, HRWRAs are used to achieve the required workability at lower w/cm and optimize the total cementitious content.

There are HRWRAs that are specifically developed for shotcrete mixtures. Shotcrete is commonly used in tunneling and mining for initial support, final lining, or both. In tunnels and mines, shotcrete is sometimes pumped long distances; this requires the shotcrete mixture to be highly pumpable, homogenous, and workable. These shotcrete HRWRAs, apart from water reduction, also have the property to improve workability retention, reduce concrete viscosity, aid pumping, and reduce chances of segregation. They are also compatible and perform better in conjunction with alkali-free shotcrete accelerators (Chapter 6).

16.8.5 Extended set-control admixtures—Extended set-control admixtures (ESCs), also known as hydration-controlling admixtures, are used in shotcrete to extend the workable life of concrete up to several hours or days, if necessary (Chapter 9).

16.9—Admixtures for manufactured concrete products

16.9.1 Introduction—Admixtures for manufactured concrete products (MCPs) are used to add production efficiency, improve or modify surface texture, enhance and maintain visual appeal, and provide value-added performance benefits. A low slump to zero slump concrete consistency enables freshly-formed products to be dimensionally stable upon shaping. Admixtures for these machine-made, mass-produced elements should work within this narrow window of operation and not interfere with the various fabrication processes. There are currently no applicable performance standards for admixtures used in these applications.

16.9.2 Materials—Admixtures for MCPs apply to a wide range of chemistries and applications. Materials most commonly used are 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.

16.9.3 Applications—Admixtures for MCPs are used in a number of applications, including production of blocks, pavers, paving slabs, roofing tiles, dry-cast pipe, hollow-core planks, segmental retaining wall units, and other miscellaneous dry-cast products.

16.9.4 Effects—Additions of admixtures for MCP individually or in combination generally contribute to increased plant efficiency, production rate, uniformity, increased compressive strengths, and durability of MCPs. Each group of admixtures provides its own unique benefits in the production of MCP units. Plasticizing chemistries play an important role in reducing production costs, modifying surface texture, improving color consistency, and providing improved uniformity from piece to piece.

Accelerators are used with, or in place of, standard accelerated curing practices. In warmer climates, they can be used during the cool season where live steam or radiant heating
CHAPTER 17—ADMIXTURES FOR FLOWING CONCRETE

17.1—Introduction

ASTM C1017/C1017M defines flowing concrete as “concrete that is characterized as having a slump greater than 7-1/2 in. (190 mm) while maintaining a cohesive nature...” Flowing concrete should be obtained through the use of a plasticizing admixture, conforming to ASTM C1017/C1017M, and a uniform combined aggregate gradation. The uniform combined aggregate gradation will usually produce a cohesive, workable concrete mixture. Plasticizing admixtures are typically mid-range water-reducers (MRWRs) or high-range water-reducers (HRWRs) conforming to ASTM C494/C494M Types F and G (refer to Chapter 6). Depending on travel time, temperature, and mixture, the concrete may need to be redosed on the jobsite because adding water could result in lower-quality concrete. Concrete can be delivered to the job site at an initial slump of 2 to 3 in. (50 to 75 mm) and the plasticizing admixture then added to produce flowing concrete. The preferred practice is adding the plasticizing admixture at the concrete batch plant so that the concrete arrives at the job site with the slump required for placement. The dosage required to achieve a flowing consistency varies depending on the cementitious material, the initial slump, \( w/cm \), temperature, time of addition, and concrete mixture proportions.

17.2—Materials

Admixtures used to achieve the flowing concrete should meet the requirements of ASTM C1017/C1017M Type I or Type II (retarding). Commonly used admixtures for the production of flowing concrete include mid-range water reducers (MRWRs) and high-range water reducers (HRWRs) (Chapter 6). Other admixtures include viscosity-modifying admixtures (VMAs) (Chapter 11), set retarders (Chapter 8), set accelerators (Chapter 7), and workability-retaining admixtures (Chapter 10).

17.3—Selection and evaluation

When deciding to produce and use flowing concrete, consider the type of admixture to be selected. Factors include:

a) Type of construction
b) Placement and consolidation techniques (pumping versus crane and bucket, internal versus external vibration)

c) Restrictions imposed on the chloride-ion content
d) Concrete mixture proportions and order of addition
e) Admixture-dispensing equipment
f) Concrete delivery time
g) Ambient temperature
h) Form, geometry, and reinforcing bar spacing

The proposed flowing concrete mixture should be used initially on noncritical work or in a test pour so that proportions and procedures can be verified before the mixture is used in the areas requiring flowing concrete. The proportions of the various concrete ingredients can be adjusted and the dosage or the type of admixture varied to achieve an acceptable final slump, rate of slump loss, and setting characteristics. If the plasticizing admixture is to be added at the jobsite, an accurate means of introducing the admixture into the concrete mixer should be ensured. Additionally, when plasticizing admixtures are added to the truck, the truck drum should be reversed to bring fresh concrete to the back of the drum and the admixture placed onto the concrete rather than pouring admixture onto the empty fins. This ensures that all of the admixture is incorporated into the concrete mixture. Adequate mixing speed and revolutions should be maintained as defined in ASTM C94/C94M. Accurate measurements of the admixture dosage are critical, and proper mixing is essential to realize the full benefit of the admixture. The required mixing time or revolutions to adequately disperse the admixture throughout the load should be known. In addition, a redosing chart that provides the quantity of admixture to be added per cubic yard (meter) to increase the slump in the required increments along with mixing time should be on site from the concrete producer.

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

a) Results from jobs where the admixture has been used under good technical 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 of the admixture

ASTM C1017/C1017M provides compliance with specifications under controlled conditions of temperature, fixed cementitious material content, slump, and air content, using aggregates graded within stipulated limits. This standard requires certain minimum differences in concrete strength, range of setting time, and requirements regarding other aspects of performance such as shrinkage and resistance to freezing and thawing.

17.4—Applications

Flowing concrete is commonly used in areas requiring increased placement rates, such as slabs, mats, and columns, and in congested locations where the finished concrete surface is aesthetically sensitive and is unusually shaped or heavily reinforced (Nmai and Violette 1996). It can be used in areas of limited access or where the increased horizontal movement of the concrete is desirable. Flowing concrete is useful for pumping because it reduces pumping pressure and increases both the rate and distance that the concrete can be pumped. It is useful for projects that require rapid form cycling with an increased volume of concrete placed per day. Coupled with a low \( w/cm \), the early strengths required for stripping or post-tensioning can be achieved; an example is flowing concrete with a low \( w/cm \) obtaining a compressive strength of 3000 psi (20 MPa) or greater in 24 hours.

Flowing concrete is often desirable for use in mass placements. The cement content can be kept low, which minimizes...
heat development, and the lower water content reduces drying shrinkage. The plasticizing admixture does not lower the temperature rise in concrete except as a result of reducing cement content. The early temperature-rise characteristics can be modified with the use of the retarding version of the plasticizing admixture (Type II) or in combination with a conventional water-reducing retarding admixture (Type D).

High-performance concrete (HPC) has higher-than-normal compressive strength, reduced permeability, increased durability, or reduced drying shrinkage. The necessity to reduce the w/cm to 0.45 or lower to produce HPC while achieving a placeable concrete requires the use of a high-range water-reducing admixture (HRWRA) (Aitchin and Neville 1993). Concrete with a low w/cm and a compressive strength higher than 8000 psi (55 MPa) can be produced as flowing concrete. Flowing concrete, being easier to consolidate, also contributes to the proper bond between reinforcing steel and concrete in areas where reinforcement is congested.

Using plasticizing admixtures to increase slump from 2 to 3 in. (50 to 75 mm) to 7.5 to 10 in. (187.5 to 250 mm) or greater also reduces the amount of cement required to achieve a particular strength. Because concrete is seldom placed at a slump level of 2 to 3 in. (50 to 75 mm), the additional water required to raise the slump should be matched with an increase in the cement content if the strength and w/cm were kept constant. The higher paste content would result in a concrete with a higher shrinkage and permeability, thereby reducing concrete durability.

**17.5—Proportioning concrete**

When admixtures are evaluated in laboratory trial mixtures before job use, the series of mixtures should be planned to provide the necessary project information. Assuming that specification compliance has been established, the tests need not follow ASTM C1017/C1017M test conditions for slump, air content, and cementitious material content. The test conditions, however, should be consistent with the project requirements for target slump, air content, setting time, and strengths at various ages. The trial mixtures should be made with the same materials, particularly cementitious materials that will be used on the jobsite, and should simulate the site conditions as closely as possible. Temperature is particularly important to setting times and early strength development. Trial mixtures can be made with a starting slump and air content in the specified range. The dosage of the plasticizing admixtures can be varied to achieve different slump increases. This activity will help in creating dosage guidelines to be used during the project, as mentioned previously. If allowed, the initial slump may also be varied. The specified w/cm should be maintained in each case, and a range of slumps can be reviewed. In this manner, the optimum mixture proportions can be selected and the desired results achieved.

A concrete mixture usually needs reproportioning when a plasticizing admixture is added to achieve flowing concrete. Procedures for proportioning and adjusting concrete mixtures are covered in ACI 211.1 and ACI 211.2. The appendix to ACI 211.1 provides procedures and guidelines for proportioning coarse and fine aggregates to produce a more workable concrete mixture that is less susceptible to segregation and requires a lower paste content to produce a required slump. Fine-to-coarse aggregate ratio may require adjustment to ensure that sufficient fines are present to allow a flowable consistency to be achieved without excessive bleeding or segregation. Increasing the cement content or adding other fine materials, such as pozzolan or slag (ACI 233R), might also be necessary. In addition, rheology-modifying admixtures (RMAs) and viscosity-modifying admixtures (VMAs) can be used in conjunction with or in partial substitution of reproportioning. Because 0.5 gal. (2 L) or more of plasticizing admixture is customarily used per cubic yard (meter) of concrete to produce flowing concrete, water in the admixture should be accounted for when calculating w/cm and the effect on mixture volume. The air content and setting time of job concrete differ considerably from those of laboratory concrete with the same materials and mixture proportions. Therefore, adjusting the proposed admixture dosages on the jobsite before its use in the required locations may be necessary.

**17.6—Effects on fresh and hardening concrete**

17.6.1 **Setting time**—ASTM C1017/C1017M Type I admixtures are required to have a negligible effect on initial and final setting times. At increased concrete mixture temperatures, the setting time of concrete containing the Type I admixture is decreased. A Type II admixture can reduce slump loss significantly and retard the initial setting time of the concrete. Retarding the setting time of slabs, pavement, and deck concrete can produce excessive plastic and shrinkage cracks if the concrete is not properly protected and cured. In formed concrete, a retarded setting time can produce more pressure on the forms. It is common to use set-accelerating or set-retarding admixtures in combination with ASTM C1017/C1017M Type I admixtures to produce the desired setting characteristics of flowing concrete. The influence on setting time is highly dependent on the specific dispersant chemistry used in the high-range water-reducing admixture (HRWRA), as well as the dosage of the admixture. Most polycarboxylate-based HRWRAs have a minimal retardation effect on the concrete (Collepardi and Valente 2006).

17.6.2 **Workability and finishing**—When concrete mixtures are properly proportioned, flowing concrete is extremely workable without excessive bleeding and segregation. The upper slump limit at which flowable concrete still remains cohesive can be determined by testing the mixture before use. Segregation and bleeding can be reduced by increasing the fine-to-coarse aggregate ratio, improving the aggregate grading, adding other fine material, or through the use of rheology-controlling, viscosity-modifying admixtures (VMAs), or both. Producing a uniform combined aggregate gradation in accordance with ACI 211.1 will greatly reduce or eliminate segregation. Excessive bleeding can be reduced by air entraining the concrete mixture. Flowing concrete should be vibrated to achieve proper consolidation (ACI 309R). The response of flowing concrete to machine finishing is similar to that of conventional concrete made...
with the same ingredients without an HRWRA. Successful finishing requires proper timing. If a concrete contains too much fine aggregate, the air content is too high, or both, the surface of the concrete may tend to dry before it sets. This condition could cause the concrete to feel rubbery or jelly-like and cause finishing problems because of its stickiness and rolling. The problem of excessive air content in concrete used in floor slabs is particularly apparent when the initial machine-finishing operations begin. The air content of trowel-finished floors should not exceed 3 percent.

17.6.3 Rate of slump loss—The rate of slump loss in flowing concrete containing an HRWRA will be affected by the: type and dosage of HRWRA used; simultaneous use of an ASTM C494/C494M Type A, B, or D admixture; type and brand of cementitious materials; and concrete temperature. Workability-retaining admixtures (Chapter 10) provide workability (slump) retention without retardation when used in combination with mid-range water-reducing admixtures (MRWRAs) and HRWRAs. These factors are not the only ones affecting slump loss, but they can typically be controlled by the user (Ramachandran and Malhotra 1984). Ambient temperature is not as controllable, but can have a dramatic effect on the performance of an HRWRA. Ravina and Mor (1986) have shown that the higher the HRWRA dosage, the lower the rate of slump loss. Each product has an operating range beyond other properties of the concrete that might be affected; if this range is exceeded to further reduce the slump loss, results could include changes in initial setting times, segregation, or bleeding.

As a result, in HRWRA technology and the numerous products available, it is advantageous to describe these products not only by the requirements of ASTM standards, but also by method of addition. Although both specifications for HRWRAs (ASTM C494/C494M; ASTM C1017/C1017M) mention slump loss, neither currently requires tests for slump-loss characteristics. When some HRWRAs are added at the jobsite, the concrete exhibits moderate to rapid slump loss and normal or retarded initial setting times. HRWRAs designed to be added at the batch plant can extend slump retention in concrete (Collepardi and Corradi 1979) along with either normal or retarded initial setting times. The difference in performance is not an indicator of admixture quality, but more that certain admixtures are more appropriate for other construction conditions.

17.6.4 Additional dosages—An additional dosage of plasticizing admixture should be used when delays occur and the required slump has not been maintained. Two additional dosages have been used with success; more dosages generally are less effective. Redosing with an HRWRA after approximately two dosages with the same amount of HRWRA will not produce the same increase in workability and slump gain. Furthermore, retarded set times may be produced. Not every HRWRA can be redosed; however, nonretarding HRWRAs can be redosed several times. In general, the compressive strength level is maintained or increased and the air content is decreased. Therefore, if air entrainment is a concern, it should be checked after the concrete has been redosed and returned to its intended slump.

17.6.5 Heat of hydration and temperature rise—The total amount of heat produced by hydration is not changed if the cementitious material is not altered. The rate of evolution, however, can be altered. If the use of flowing concrete involves the use of lower cementitious content, less heat will be evolved.

17.7—Effects on hardened concrete

17.7.1 Strength—Because flowing concrete is often batched initially with a water content resulting in a slump of 2 to 4 in. (50 to 100 mm), the w/cm is lower than that of conventional concrete with a similar cementitious material content and a 5 in. (125 mm) slump, improving the strength. Flowing concrete often is stronger than conventional concrete at the same w/cm, due to increased dispersion, resulting in a more efficient cement hydration. The flexural strength of flowing concrete is not significantly changed from that of the initial concrete with the same w/cm at a lower slump.

17.7.2 Shrinkage and creep—The drying shrinkage of low-slump concrete is approximately the same as that of flowing concrete with the same w/cm and lower water content (Gebler 1982). If the cement content is kept constant to produce flowing concrete with a lower water content, then drying shrinkage can be reduced. If both cement and water contents are reduced, then drying shrinkage can be reduced. When compared with concrete with the same w/cm, concrete with an HRWRA shows little change in creep characteristics (Brooks et al. 1981; ACI 209R). Refer to Chapter 6 for discussion on shrinkage and creep.

17.7.3 Resistance to freezing and thawing—Conventional and flowing concrete with the same w/cm and a comparable air-void system exhibit a similar resistance to freezing and thawing. Compared with conventional concrete, higher dosages of air-entraining admixture usually are required for flowing concrete to maintain proper air content. For a given air content, the air-void system may have larger spacing factors and a decrease in the number of voids per unit length compared with the control concrete; however, satisfactory resistance to freezing and thawing has been achieved in most cases. As with any air-entrained concrete, the air content in the field should be checked so that the air-entraining admixture dosage can be modified to keep the air content in the specified range.

17.7.4 Permeability—Flowing concrete with a w/cm below 0.40 can be placed easily; therefore, the resultant concrete, if properly cured, can have extremely low permeability and good resistance to the penetration of aggressive solutions. Resistance to chloride penetration is similar to, or slightly better than, that of conventional concrete with the same w/cm (Lukas 1981). When the admixture is used to reduce the w/cm, resistance to the chloride penetration is even greater. Flowing concrete shows better consolidation, reduced bleeding, and increased cement hydration—all of which contribute to lower permeability.

17.7.5 Bond—Flowing concrete can improve bond strength to reinforcing steel when compared to similar concrete with a 4 in. (100 mm) slump (Collepardi and Corradi 1979). Brettman
et al. (1986) found that flowing concrete showed no change in bond strength compared with lower-slump concrete with an equal \( w/c \), providing the concrete was vibrated and set rapidly after consolidation. Bond strength in reinforced concrete beams having equal \( w/c \), however, was decreased if the flowing concrete’s setting time was delayed. Proper consolidation around the reinforcement is more easily achieved with flowing concrete, but adequate vibration is needed.

17.8—Quality assurance and batching
17.8.1 Field control of concrete containing high-range water-reducing admixtures—For both plant-added or jobsite-added high-range water-reducing admixtures (HRWRAs), ensure from batch records that the water content and \( w/cm \) are within specification. HRWRAs can be added at the plant or jobsite and thoroughly mixed into the concrete to produce the desired workability while also maintaining mixture stability. For air-entrained concrete, the air content also should be checked at the point of discharge from the transportation unit. If the flowing concrete is pumped into place, the air content should be measured at the point of discharge into the forms. Placing concrete with a pump can significantly impact air content (Whiting and Nagi 1998). Therefore, it may be necessary to measure air content at the point placement to determine the difference from that delivered. Rate of slump loss, initial setting time, and early and final strength results may require mixture adjustments. Slump loss and setting characteristics can be adjusted by changes in the HRWRA dosage or concurrent use of accelerating or retarding admixtures. When the concrete placement is abnormally slow, the temperature is high, or both, the use of an HRWR Type G admixture or a Type F admixture in conjunction with a workability-retaining admixture can be desirable. However, care should be taken with mixture proportions and ambient conditions to ensure that excessively long setting times do not result. Because variations in cement composition, aggregate grading, or both, can cause significant variations in the flowing-concrete characteristics, these changes should be minimized. When pumping, flowing concrete should be placed in accordance with ACI 304.2R and consolidated in accordance with ACI 309R.

CHAPTER 18—ADMIXTURES FOR SELF-CONSOLIDATING CONCRETE (SCC)

18.1—Introduction
Self-consolidating concrete (SCC) has many potential benefits, offering the opportunity to significantly reduce construction time and labor, achieve improved formed surface finish, and help ensure acceptance of architectural treatment (Daczko 2012). As consolidation is not required, construction problems related to inadequate consolidation can be avoided. Given the extensive discussion in ACI 237R, this chapter will emphasize admixture types and selection, and treat other issues only as needed for clarity. The reader is referred to ACI 237R for basic principles in detail and to understand several terms used herein.

Fig. 18.2.1a—Stress-strain diagram.

18.2—Materials for self-consolidating concrete admixtures
Both high-range water-reducing admixtures (HRWRAs) and viscosity-modifying admixtures (VMAs) used for self-consolidating concrete (SCC) (Daczko 2012) are discussed in this section. Refer to Chapter 6 for additional information on HRWRAs and Chapter 11 on VMAs. Although other admixtures are used, this chapter addresses these with respect to compatibility only.

18.2.1 SCC rheological principles—Details of SCC rheology are available in ACI 237R and in the literature developed in the last 10 years (Wallek 2003; Nielsson and Wallek 2003; Utsi et al. 2003; ACI 238.1R). A simplified outline is provided to enable a discussion of the impact of various admixture types.

A conceptual stress-strain diagram of several types of concrete is given (Fig. 18.2.1a). Concrete approximates a Bingham fluid, in that it shows a yield stress, below which it will not move. This is represented as the intercept on the y-axis. The slope of the stress-strain curve is the plastic viscosity, the resistance of the concrete to moving faster. Concrete workability, whether measured by slump (conventional concrete) or slump flow (SCC), is related to both yield stress and plastic viscosity. Low-slump concrete has a higher yield stress, whereas high-slump concrete has a lower yield stress. As seen in Fig. 18.2.1a, adding water to concrete lowers both the yield stress and plastic viscosity. Low-slump concrete has a higher yield stress, whereas high-slump concrete has a lower yield stress. As seen in Fig. 18.2.1a, adding water to concrete lowers both the yield stress and plastic viscosity, whereas adding HRWRAs tends to lower the yield stress with little impact on plastic viscosity. Flowing concrete made with HRWRAs, therefore, can be stable at high slumps (low yield stresses) where concrete with the same slump achieved with water cannot.

To achieve required flow and filling ability, SCC should have even higher fluidity, yet continue to have enough cohesion to resist segregation and to pull aggregate through close gaps between reinforcing bars (so-called passing ability). To achieve these properties, SCC should have a very low yield stress, but higher plastic viscosity than conventional concrete would at such low yield stress. These yield stress-plastic viscosity relationships can be represented with the plastic
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Figure 18.2.1b—Yield stress-plastic viscosity.

Figure 18.2.1c—Yield stress-plastic viscosity.

Figure 18.2.1d—Yield stress-plastic viscosity.

Figure 18.2.1e—Yield stress-plastic viscosity.

Viscosity on the x-axis and the yield stress on the y-axis, as shown in Fig. 18.2.1b (Tattersall and Banfill 1984).

To better understand what is involved in moving the concrete rheology to the required region in this diagram, consider the impact of simply adding water to decrease yield stress to the level needed for SCC, as shown in Fig. 18.2.1c. Yield stress is reduced, but plastic viscosity is reduced as well, and the concrete becomes highly segregating.

If instead of water, a normal HRWRA is added without restructuring the mixture proportions, the result would be a decrease in yield stress with relatively small changes in plastic viscosity, as shown in Fig. 18.2.1d.

One of the typical means of making SCC is to proportion a high-fines mixture. The net effect of adding higher fines is to increase interparticle attraction, thus increasing the plastic viscosity and concrete cohesion, as shown in Fig. 18.2.1e. Increased cohesion also improves the passing ability of the mixture, which is the ability of the paste to pull coarse and fine aggregate through narrow spaces in the formwork.

Increased cohesion and plastic viscosity is also achieved through use of VMAs, which are described in Chapter 11. Either high-molecular-weight water-soluble polymers or dispersions of very fine particles will function much like adding extra fines. They permit design of SCC with lower total fines content, which could be beneficial technically, economically, or both.

Another key rheological parameter is thixotropy, which is the reversible buildup of interparticle attraction while a concrete is at rest. In practical terms, this implies that when a concrete is placed in motion at a fixed shear rate, the viscosity decreases with time. Or, conversely, the viscosity increases with time when the concrete is at rest. Thus, a thixotropic material will behave with lower viscosity while under movement than after a period of rest. Therefore, if two SCC mixtures display the same yield stress and the same plastic viscosity while under movement, the one displaying higher thixotropy will be more resistant to static segregation. Mixture thixotropy, however, should also be considered based on concrete placement methods and how quickly successive batches will be placed to ensure that pour lines are not created.
In recent years, developments in the design of high-range water-reducing polymers and formulation of these with other materials has permitted the development of admixtures that allow the reduction in yield stress while increasing plastic viscosity, as shown in Fig. 18.2.1f. These permit formulation of SCC with lower powder contents, a reduction in the use of additional VMAs, and, in some cases, increased thixotropy. In field applications, the slump flow (ASTM C1611/C1611M) can be used to estimate the yield stress (higher slump flow = lower yield stress) (Chidiac et al. 2006) whereas the plastic viscosity is approximated by the $T_{90}$ time (longer time = higher plastic viscosity). Concrete is generally considered to be an SCC when the slump flow lies between 22 and 30 in. (550 and 750 mm). $T_{90}$ times from 2 to 10 seconds are generally used, depending on applications (ACI 237R).

Passing ability is measured by an adaptation of the slump flow test, called the J-ring, in which a circle of bars surrounds the slump cone when it is raised. The spread with the ring in place is compared to that without; a concrete with high passing ability will have similar slump-flow diameters. Many other tests have also been developed to measure passing ability, but they are beyond the scope of this discussion. There is currently no accepted field test method for measuring thixotropy.

The stability of an SCC mixture is estimated by the Visual Stability Index, a comparative appraisal of the degree of segregation observed in the slump flow patty (ASTM C1611/C1611M). A rating of 0 is highly stable, 1 is stable, 2 is unstable, and 3 is highly unstable. This measures the tendency for paste to separate from the aggregate during and after the slump flow measurement. When the paste is seen to readily separate, steps should be taken to increase the paste viscosity itself, either by adding powder, reducing water, changing to a more cohesive HRWRA, or adding a VMA. Another static stability test, the Column Segregation Test (ASTM C1610/C1610M) provides a more quantitative assessment of stability. In this test, a pipe is filled with SCC, allowed to rest a fixed length of time, and the top fourth and bottom fourth of concrete separated and washed out, to enable comparison of the coarse aggregate content. This measures the tendency for the aggregate to settle in the concrete, which may not be directly comparable to the paste stability, but is critical for concrete to be considered self-consolidating.

**18.2.2 Critical attributes of SCC admixtures—**Admixtures for SCC should be able to impart very strong high-range water reduction characteristics (±30 percent) giving large slump flows while increasing plastic viscosity to impart stability and passing ability, and, in some applications, thixotropy. In materials proportioning and admixture selection for SCC, selection of the appropriate SCC admixtures depends on the degree of SCC characteristics required and the starting constituents of the concrete mixture. The more well-graded and shaped the aggregates are, the lower the water demand, and the more powder content there is in the mixture, the less critical the admixture selection. ACI 237R cites three methods of SCC formulation: 1) high powder content with HRWRAs; 2) low powder content with VMAs; and 3) moderate powder content with HRWRAs and low VMA doses. There is actually a wide range of approaches, trading off the various attributes and costs of base materials selection and control, and admixtures from which to choose.

Other properties required for reliable production of SCC include resistance to loss of slump flow for adequate filling ability post-delivery, including possible delays on the jobsite. Newer SCC admixtures can ensure long retention of needed slump flow. Use of retarders is often effective in prolonging slump life, but the potential increase in setting time may influence pour rates in situations where form pressure restrictions exist. Long retardation periods can also affect in-place segregation. Workability-retaining admixtures (Chapter 10) provide workability (slump) retention without retardation when used in combination MRWRA and HRWRA.

Significant progress has been made in water tolerance, which is needed so that variances due to changing water demand of the materials, or moisture content of the aggregates, do not cause the SCC to segregate. Recent work (Corman 2005) has shown that virtually any level of water tolerance is now technically possible (Fig. 18.2.2).

**18.2.3 Self-consolidating concrete HRWRAs—**As outlined in ACI 237R, the principles of mixture proportioning for SCC involve reducing the amount and size of coarse aggregate to improve blocking resistance, increasing the paste content to improve cohesion, and use of HRWRAs to reduce the yield stress to give the needed slump flow to achieve desired filling ability. In high-paste, high-fines situations, normal HRWRAs have been found to work successfully. Thus, it is possible to use materials in Categories 1 through 6 of 6.2.2 to make SCC. SCC based on conventional naphthalene sulfonate HRWRAs was used in high volumes in major projects in the 1980s, made possible due to very high cementitious contents and use of silica fume (Kuennen 1996).

In the last 20 years, the development of polycarboxylate-based HRWRAs has improved the ease of SCC production, as polycarboxylate-based HRWRAs tend to improve cohesion relative to naphthalene or melamine-based HRWRAs.
SCC admixtures have been developed by composing blends of different polycarboxylate polymers that have different rates of adsorption on the powder substrates. By adjusting the ratio of different polymers, slump flow in many cases can be maintained as long as is practically needed—up to several hours with little or no retardation. These may actually allow for an increase in slump flow over time. Other materials can be included to adjust performance. Different products will impart a decreased tolerance to moisture variation (Koyata and Cormann 2005).

18.2.4 Self-consolidating concrete viscosity-modifying admixtures—VMAs is another major admixture class used for SCC. They work to mimic the effect of higher fines—substituting polymer interaction or ultra-fine particle interaction to achieve the cohesive effect achieved by much higher levels of conventional fine particles. This allows achievement of stability and passing ability at lower levels of cement or cementitious materials. Refer to Chapter 11 for more information on VMAs. The addition of a VMA to a stable SCC mixture can also provide robustness to the mixture, which refers to the ability of the proportioned mixture to maintain excellent performance if mixture constituents change or if aggregate moisture contents fluctuate.

18.3—Selection and evaluation

Self-consolidating concrete (SCC) is much more sensitive to changes in materials, including high-range water-reducing admixtures (HRWRAs) and viscosity-modifying admixtures (VMAs), than conventional concrete. The ultimate mixture proportion of an SCC depends on the admixture in a fundamental way. Once a set of materials is qualified, caution should be used, including requalification, before changing any constituents. In developing mixtures, a basic understanding of the available aggregates will help in choosing the types of admixtures to be evaluated. If the aggregates are very well graded and shaped, and if relatively high powder contents are acceptable, a conventional polycarboxylate HRWRA without a VMA may be acceptable. As the aggregates depart from ideality, becoming either gap-graded or harsh and angular, the water demand will rise and admixtures imparting more cohesion will be necessary. Generally, either a conventional polycarboxylate HRWRA with a VMA or a special SCC HRWRA will be needed. When the aggregates are far from ideal, or when powder content is limited—for instance, due to considerations for shrinkage—both a special SCC HRWRA and VMA may be necessary. Finally, when production considerations indicate control of water may be a limiting factor for SCC production, those SCC admixtures imparting reduced sensitivity to water may be needed.

18.4—Proportioning concrete

As reviewed extensively in ACI 237R, self-consolidating concrete (SCC) proportioning starts with understanding the anticipated application to which the concrete will be placed. Greater element intricacy, denser reinforcement, and higher demand on surface finish all require higher slump flow. Once the target application is known, the coarse aggregate size is chosen. One widely used starting point is to have 50 percent of the bulk volume occupied by the coarse aggregate. Next, the powder content is chosen with higher levels usually selected for higher slump flows, as this both increases cohesion and paste density. Use of supplementary cementitious materials (SCMs) or fillers can reduce the cement content needed to reach required powder levels. Higher paste density helps because the difference in density between the paste and aggregate is the driving force for aggregate settlement, and stability is improved at higher paste density. Finally, the admixture or combination of admixtures is chosen, and then the trial mixture is made, tested, and adjusted. Frequently, it is useful to obtain slump results prior to SCC admixture addition to provide a baseline reference for tracking of material changes.

Understanding the principles reviewed are critical; as higher slump flow is needed, stability becomes more difficult to achieve. Well-graded and shaped aggregates will result in lower water volumes, resulting in a decreased need for very high powder contents. It then becomes a trade-off between the cost and difficulty of controlling aggregate grading and shape, and the increased admixture cost of a special SCC high-range water-reducing admixtures (HRWRAs), added viscosity-modifying admixtures (VMAs), or both. On-site test placements are required to verify optimum slump/flow, stability, setting time, and finish, if required.

18.5—Effects on fresh and hardening concrete

The major effect of self-consolidating concrete (SCC) admixtures on fresh concrete is on the rheology (18.2.1). Some SCC admixture combinations can retard slightly, so combinations with other admixtures, which can cause retardation, should be carefully checked. Air entrainment can be difficult if the mixture becomes so fluid that insufficient paste viscosity remains to retain the air. Switching to a more cohesive high-range water-reducing admixture (HRWRA), adding a viscosity-modifying admixture (VMA), or increasing fines may be necessary. In some combinations of materials, air void systems may be found to be too coarse,
in which case changing the air-entraining admixture or the HRWRA might be needed.

Until a consensus model is developed to predict SCC formwork pressures, expect SCC initially to produce full hydraulic pressure to the forms. Thixotropy will reduce this pressure prior to actual setting, but the actual effect in the forms can also be altered by the placement method, as fresh SCC being placed on top of SCC already undergoing thixotropic set may exert full hydraulic pressure on the forms (Brameshuber and Uebachs 2003; Fedroff and Frosch 2004; Billberg et al. 2005) For now, prudent practice is to establish pour rates that do not exceed the pressure rating of the forms.

18.6—Effects on hardened concrete

As reviewed in ACI 237R, self-consolidating concrete (SCC) has largely been found to behave as normal concrete is expected to, given the substantial differences in proportions. That is, the admixtures have not altered the performance outside the expected envelope. Although SCC generally has very high powder and paste contents, which lead to high strength, it may also lead to higher shrinkage, creep, temperature rise, and a greater potential for cracking. Paying close attention to aggregate selection to reduce water demand and using admixture systems that permit the needed rheological properties, without excessive powder contents, can reduce this tendency. Due to the low w/cm, permeability is generally low and durability is high. Frequently, strengths are much higher than required for the structural design, which can lead to issues of crack width if cracking occurs and the reinforcement level is not adequate to keep limit crack widths. In general, the hardened properties of SCC are dictated by the materials and mixture proportions. Because there is no one mixture design for SCC, a wide range of hardened properties are possible. The relationships between proportions and hardened properties follow the same rules for SCC as for conventional-slump concrete.

18.7—Quality assurance and batching

Production of self-consolidating concrete (SCC) requires significantly higher levels of plant and site quality assurance than conventional high-range water-reducing admixture (HRWRA) concrete (Daczko 2012), especially during development and initial production. In the initial proportioning process, proper selection of aggregate size, shape, and amounts; selection of paste volume and supplementary cementitious materials; and selection of admixtures is required. Quality assurance methods should be in place to assure that the materials used in initial trials are reproduced during production. Critical areas are consistency of cement and cementitious material supply, consistency of aggregate grading and shape, and control of moisture content. Adequate personnel are necessary to make adjustments in the mixture as the inevitable material changes do occur. The mixture design should be robust enough to perform well on a daily basis with the normal variations, cementitious materials, and aggregate gradation. The mixture should always be within ±2 in. (50 mm) slump flow of the target slump flow. Active communication between site quality control personnel and plant production personnel is critical to make adjustments in a timely manner.

Due to SCC’s requirement for consistency, adhering to strictly controlled batching procedures is necessary. Batching less than full mixer or truck loads can be problematic, as batching precision suffers, mixing energy changes, and the impact of extraneous material increases. Each producer will have to determine his or her ability to produce smaller loads and restrict production to the levels found to be reproducible.

Water control is essential. The mixer or each truck should be empty prior to batching. As little as 1 gal. of water/yd³ (5 L of water/m³) may be the difference between stable and segregating SCC. All possible measures to control and adjust for aggregate moisture should be implemented. In central mixers, using the mixer ammeter to set a baseline amperage that produces good SCC after admixture dosage, and then controlling to that amperage prior to admixture addition, can be helpful. Changes in that number can reflect loss of moisture control. With truck mixers, occasionally confirm moisture control by measuring the slump before SCC admixture addition.

Recognize that some SCC admixtures take time to develop slump flow. This may be more important with materials that impart higher mixture stability. Determine the time for the materials being used, and make sure that adequate mixing time is given. Reduce mixing speed to prevent excessive splashing. A folding action is desirable. This may be critical in controlling air generation and stability. Due to the very fluid nature of SCC, reduction in batch size may be required to limit spillage.

CHAPTER 19—ADMIXTURES FOR VERY COLD WEATHER CONCRETE

19.1—Introduction

There has been increased need to place concrete under conditions where it may freeze before gaining significant strength. Freeze-resistant admixtures have been used in the former Soviet Union since the 1950s to suppress the freezing point of concrete and permit placement and curing of concrete below the freezing point of water (Brook and Ryan 1989). Typically, nonchloride set accelerators are basic ingredients of freeze-resistant admixtures. When used for this purpose, dosage rates are much higher than those used at temperatures above freezing.

For concrete cured at low temperatures, early strengths are low, even though strengths can be similar to normally cured concrete at later ages. Several admixtures made from nonchloride accelerators were shown not to cause corrosion of embedded reinforcing steel (U.S. Army Corps of Engineers 1994). Nitrite salts reduce corrosion potential when used in amounts suitable for anti-freeze performance. Proprietary accelerating admixtures that provide water-reduction and accelerate hydration down to 20°F (−7°C) without harmful side effects are available (Brook and Ryan 1989). Sodium and potassium salts, however, should not be used with potentially reactive aggregates due to an increased risk of alkali-silica reaction (ASR), nor should they be used
in concrete subject to wetting and drying in an aggressive, marine, or sulfate environment. Other admixture systems not included in the U.S. Army Corps of Engineers (1994) work may provide similar anti-freeze behavior without the benign corrosion impact. Be sure to obtain documentation from the admixture supplier that the accelerating compounds are noncorrosive at the high end doses required for subfreezing temperatures with concrete containing embedded steel.

The U.S. Army Corps of Engineers (1994) identified combinations of commercially available admixtures to allow fresh concrete to fully cure while its internal temperature is below 32°F (0°C) without harming its performance compared with that of normal concrete cured at normal temperatures (Korhonen et al. 2004). Refer to ASTM C1622/C1622M for cold-weather admixture systems.

19.2—Materials

Currently, cold-weather admixture systems are made by using admixtures that meet ASTM C494/C494M requirements or that are commercial products otherwise accepted by industry practice. The admixtures are mainly selected for their individual abilities to depress the freezing point of water or to accelerate the hydration rate of cement at low temperatures. When dispensed separately into concrete, they should be compatible with one another so as to not promote corrosion. The admixture system should conform to ASTM C1622/C1622M. In recent studies, eight admixture systems were identified that, during laboratory tests and field trials, yielded fresh concrete with a depressed freezing point of 23°F (~5°C) or lower and had reasonable transit life and good jobsite workability (Korhonen et al. 2004).

19.3—Selection and evaluation

Each cold-weather admixture system consisted of up to five commercial products:

1) Water reducers (ASTM C494/C494M Type A and F) to lower the water content in concrete while maintaining workability
2) Accelerators (ASTM C494/C494M Type C and E) to decrease the time of setting and aid in early strength gain as well as providing some freezing point depression
3) Retarders (ASTM C494/C494M Type B) to sometimes assist if early setting is a problem
4) Corrosion inhibitors
5) Shrinkage reducers, not so much for their implied properties, but for their added freezing point depression

19.4—Proportioning concrete

To proportion a concrete mixture that can gain appreciable strength at temperatures below 23°F (~5°C), begin with a standard winter concrete mixture design that is workable, durable, and strong. Typically, mixture designs that contain at least 610 lb/ yd³ (359 kg/m³) of cement, 0.45 or lower w/ cm, and adequate entrained air are acceptable. Converting standard winter concrete into cold-weather concrete simply requires adjusting the amount of mixing water to account for the water in the admixtures and defining when each admixture should be dispensed into the concrete.

19.5—Batching

Before cold-weather concrete is placed, it should be confirmed through a series of trial batches that prove a given cold-weather admixture system can produce concrete of acceptable workability and air content. Trial batches help determine the best timing for the addition of each admixture into the concrete. Several 3 to 5 yd³ (2.3 to 3.8 m³) trial batches should be made to confirm mixture proportions and reveal how the concrete behaves during each stage of the process. Use cold water for all batching operations to create an initial mixture temperature of 50 ± 3°F (10 ± 5°C). Higher temperatures tend to cause cold-weather concrete mixtures to stiffen too rapidly. Obtain periodic slump measurements, air contents, and concrete temperature readings to establish that the mixture behaves as desired until it is placed and finished. Trial batches will provide an opportunity to experiment with various admixture dosing procedures and train batch plant operators, truck drivers, and the job supervisor in working with this concrete. Three admixture dosing procedures have been field-tested (19.5.1 through 19.5.3).

19.5.1 Procedure 1—Dispense the entire cold-weather admixture system into the concrete at the concrete plant. This has the advantage that once the truck leaves the plant, no further effort is required. The disadvantage, however, is that the high concentration of hydration-accelerating admixtures in these systems will cause the concrete to lose slump rapidly. Travel times should be limited to 20 minutes, but experience has shown that large slump loss could be recovered with additional plasticizer dosed into the mixture after travel times of up to 45 minutes. The mixture may have to be dosed with additional air-entraining admixture at the jobsite. Workers typically have approximately 20 to 30 minutes to work with this concrete.

19.5.2 Procedure 2—Delay dispensing the fastest-setting admixture into the concrete until it arrives at the jobsite while all others are dispensed at the concrete plant. This reduces slump loss during transit and air content could be more stable than in Procedure 1. The mixture, however, may need higher doses of high-range water-reducing admixture (HRWRA) to keep it mobile during transit. The concrete team needs to know that the mixture in transit will have a low water content and slump. Water should not be added to the mixture. Transit times of 45 minutes or more are possible. Working times of 30 minutes can be expected.

19.5.3 Procedure 3—Dispense all admixtures at the jobsite. The advantage is that the admixtures do not begin reacting with the cement until the construction crew needs the concrete. Because the admixtures contain water, however, the concrete should begin with a very low w/cm. The concrete team needs to know that the mixture in transit will be low water content and low slump. Transit times of up to 1 hour have not been a problem and working times at the jobsite have exceeded 45 minutes.

19.6—Trial placement

The proposed cold-weather concrete mixture should be used initially in a test placement so that proportions and dosing procedures can be verified before the mixture is
used in job applications. Proportions of the various concrete ingredients can be adjusted and the dosage of admixtures varied to achieve an acceptable final slump, rate of slump loss, freezing point, and setting characteristics.

19.7—Placing and finishing

The substrate against which fresh concrete is to be placed should be free of ice and snow. Although it is permissible for its temperature to be below freezing, all sources of excess water should be removed.

The behavior of cold-weather concrete in its plastic state is similar to that of high-cement-content, low-w/cm concrete. This concrete can be sticky to finish but tends to lose its stickiness as setting proceeds.

Continuously place the concrete within 20 to 30 minutes or according to the working time determined during the trial batching and trial placement tests. As the concrete is placed, immediately strike off excess concrete to bring the surface to proper elevation. Following screeding, bull float the surface to embed aggregate and smooth the surface. Be careful not to seal the surface. The magnesium float should be used with care so as not to prematurely seal the surface, which can cause delaminations. Wait until the concrete can be walked on without leaving footprints more than 1/4 in. (6.4 mm) deep before floating. A float finish followed by texturing the surface with a broom is recommended for flatwork exposed to outdoor conditions. No experience is available with hard-troweling this concrete, partly because delamination could occur at air contents higher than 3 percent.

Once finishing is complete, exposed surfaces should be protected against drying. The surface should be covered with a sheet of plastic, a spray-on curing compound, or both, as soon as the surface is tack-free. This happens quickly. Cover protruding metal with insulation because it acts as a conduit to freeze surrounding concrete. Be sure to insulate the ends of metal form ties.

19.8—Effects on fresh and hardening concrete

Cold-weather concrete mixtures are sensitive to water content when it comes to freezing-point depression. They tend to lose slump very rapidly and have set, under field conditions, within 1 hour of placement. They are sticky to finish and require detailed attention when admixtures are added into the mixing process. Air contents are less stable in cold-weather concrete compared to normal concrete. In some cases, air contents have increased within cold-weather concretes as mixing time increased whereas in other cases it decreased. One admixture has been reported that seemed to remove air from concrete (Korhonen et al. 2004). Cold-weather concrete generally does not bleed when it is properly batched, which, when coupled with its fast setting nature, allows finishing operations to begin soon after the concrete is consolidated and leveled, even in very cold weather. At very low slumps, the concretes have responded well to vibration.

19.9—Effects on hardened concrete

As with normal concrete, strength gain of cold-weather concrete depends on its internal temperature. In the labora-

try, when cooled to 23°F (−5°C) soon after mixing and then held constant at that temperature, cold-weather concrete is expected to develop compressive strength at least as rapidly as control concrete cured at 40°F (5°C). In the field, where cooling may take several days, concrete structures such as bridge curbs and pavements have been returned to service in less than 1 week (Korhonen et al. 2004). This is comparable to what occurs in the summer.

Cold-weather admixture systems have not been found to reduce the freezing-and-thawing resistance of concrete. When non-air-entrained concrete was tested in accordance with ASTM C666/C666M, Procedure B, both cold-weather and control concrete failed in a like manner well before attaining 300 cycles of freezing and thawing. When both concretes were properly entrained with air, neither concrete noticeably deteriorated after experiencing 300 cycles. In test data, cold-weather concrete generally has been more durable than control concrete.

19.10—Quality assurance

Because very high doses of admixtures are used in cold-weather concrete, adequate mixing is essential. A critical question for any concrete structure is when it will be ready for use. Although there are a number of destructive and nondestructive tests that can be used to determine this, the maturity method as reported by ACI 306R is favored.

Recognizing the freezing point of fresh concrete is critical. It is affected by the type and dosage of admixture used and the total amount of mixing water in the concrete batch. Mixing water consists of water added to the batch, occurring as surface moisture on aggregates, and in the admixtures. Although the dosage of admixture and water added to the batch can be accurately controlled, the total amount of mixing water in a batch can vary by several percentage points due to changes in aggregate moisture and the tendency of contractors to add water at the jobsite. Moisture variations are especially true if heavy snow covers the aggregate piles; the final freezing point of the concrete could be considerably different than the desired freezing point.

Until a better method is developed, a rudimentary way to measure the freezing point of fresh concrete in the field is proposed by Korhonen et al. (2004). Measuring begins by making several 2 x 4 in. (50.8 x 101.6 mm) cylindrical samples, installing thermocouples at their centers, and placing them into a picnic cooler containing dry ice. The freezing point is identified as the location on the temperature versus the time plot from the cylinders being cooled, where the initial slope of the cooling curve (the mostly linear portion above 0°C [32°F]) suddenly changes. As soon as there is a noticeable increase in temperature (a matter of tenths of a degree Fahrenheit [Celsius]) caused by the latent release of heat of fusion, that part of the curve is identified as the freezing point (Fig. 19.10). If the freezing point is not met, the concrete could be rejected, an appropriate amount of extra admixture could be added into the concrete, or the structure could be thermally protected to prevent freezing.
19.11—Cost benefit

Freeze protection is a major cost multiplier on winter concreting projects. The primary difference between protecting normal winter concrete versus cold-weather concrete against freezing is heat, temporary shelter, and the labor needed to protect normal concrete versus the admixtures needed to protect cold-weather concrete. Though cold-weather admixture systems can sometimes double the cost of ready mixed concrete, the in-place cost of cold-weather concrete is typically two-thirds the in-place cost of normal winter concrete. In those cases where elaborate temporary heated shelters have to be constructed, normal concrete construction is estimated to cost 10 times more than using cold-weather concrete without shelter (Korhonen et al. 2004).

With the relaxation of concrete placing and curing temperature limits brought on by new cold-weather concrete technology, a significant extension of the construction season is feasible. It is estimated that with the new 23°F (−5°C) limit, the concrete construction and repair season can be extended by 3 to 4 months in the United States (Korhonen et al. 2004).

CHAPTER 20—ADMITUXTURES FOR VERY-HIGH-EARLY-STRENGTH CONCRETE

20.1—Introduction

Very-high-early-strength concrete (VHESC) is designed to achieve extremely high early strengths within the first few hours after placement. Although VHESC has been produced for rapid repair of concrete structures for several years now, there is no standard definition for it. The requirement of early strength, with respect to time, differs for every project.

One application is rapid repair of concrete pavements and airport runways and taxiways. For this purpose, state agencies generally specify a minimum compressive strength of 2000 psi (13.8 MPa) or flexural strength of 400 psi (2.8 MPa) within 4 to 8 hours of concrete placement so that a facility can be reopened quickly (Kurtz and Constantiner 2004; Smith et al. 2001).

In a research study conducted in 1993 under the Strategic Highway Research Program (Zia et al. 1993), very-early-strength (VES) concrete was defined as one that produce a minimum compressive strength of 2000 psi (13.8 MPa) in 6 hours after mixing when Type III cement is used. When alkali-activated proprietary cement was used, a strength of 2500 psi (17.5 MPa) in 4 hours was required. Further, it is also necessary that the VES concrete achieve a minimum durability factor of 80 percent after 300 cycles of freezing and thawing when tested in accordance with ASTM C666/ C666M, Procedure A.

Caltrans (2008) requires 400 psi (2.8 MPa) flexural strength in 3 hours. The Port Authority of New York and New Jersey requires 4000 psi (28 MPa) in 12 hours for runways and taxiway repairs. Based on the requirements of these cases, it could be said that if concrete achieves a minimum compressive strength of 2000 psi (13.8 MPa) or a minimum flexural strength of 400 psi (2.8 MPa) within 4 to 8 hours of its placement and meets the outlined durability criteria, it can be classified as VHESC.

During the repair and rehabilitation of pavements that carry heavy traffic volumes, time is the most critical factor. In such situations, the cost of materials is less important than the costs associated with traffic diversions and the closing of pavement sections. The use of VHESC is ideal in such situations. Very-high-early-strength concrete can also be used for full-depth pavement repairs, short stretches of new pavement, bridge decks, runways, overlays, loading docks, or any slab where an owner requires minimal down time (Anderson et al. 2003).

VHESC is also commonly used by precast producers to manufacture precast concrete elements when faster turn-around of forms is required. Placing high-temperature concrete (approximately 90°F [32°C] or above) enables the in-place concrete to achieve very high early strengths within a short time. Although the material cost of VHESC is higher than regular concrete, its added value to the precast producer makes it a popular choice in the precast industry.

20.2—Materials for very-high-early-strength concrete

Very-high-early-strength concrete (VHESC) can be produced by either using an ordinary portland cement in combination with a system of chemical admixtures or by using specialty cements. Materials used to produce VHESC, in both ways, are described in 20.2.1 and 20.2.2.

20.2.1 Very-high-early-strength concrete using portland cement and admixture systems—In this method to produce VHESC, a portland cement Type I, II, or Type III can be used. The use of Type III cement, however, is more beneficial than a Type I or II cement due to its inherent ability to produce higher early strengths. Mixture proportioning of the concrete is similar to that of a conventional high-strength concrete, but generally a slightly higher cement factor and a high dosage of the set accelerator are used.

The admixture system used in VHESC requires a high-range water reducer (Chapter 6), a set accelerator (Chapter 7),
and an air-entraining admixture if freezing-and-thawing resistance is required (Chapter 5). Workability-retaining admixtures have also been used to provide slump retention without retardation in this application (Chapter 10). Fine and coarse aggregates that are locally available can be used.

VHESC is generally produced at a concrete plant and transported to the jobsite. If the transit time from plant to jobsite is lengthy, the accelerator is added when the truck arrives at the jobsite. Jobsite addition helps to avoid stiffening of concrete during transit and allows sufficient time for placing and finishing. If jobsite addition is not possible and the transit time is anticipated to be lengthy, a workability-retaining, retarding- or hydration-control admixture might be required. Use and dosage should be selected based on a successful test placement.

In the admixture system used for VHESC, a strength accelerator can be used instead of a set accelerator. A strength accelerator is an admixture that, unlike a set accelerator, does not cause an earlier set of the concrete, but dramatically increases strength gain after the concrete’s initial set occurs (Ansari et al. 1997). Use of a strength accelerator may allow the convenience of adding the admixture at the plant rather than the jobsite.

20.2.2 Very-high-early-strength concrete using special cements—VHESC can also be produced using special cements such as high-alumina cement, calcium sulfoaluminate cements, calcium fluorooaluminate cement (regulated set cement), and magnesium phosphate-based cements. Admixtures for these specialty cements are not addressed herein.

20.2.3 Early strengths of concrete—In an ordinary portland-cement concrete mixture, hydration reaction begins as soon as water comes into contact with the cement. Among the cement compounds, the rate of hydration is highest for tricalcium aluminate (C₃A) and tricalcium silicate (C₃S) followed by tetracalcium aluminoferrite (C₄AF) and dicalcium silicate (C₂S). The presence of gypsum slows the early rate of hydration of C₃A and C₂S. The rate of hydration of the individual cement compounds does not have a direct relation with the ultimate strength of the concrete. The early-age strength of concrete is primarily due to hydration of C₃A and in some part to C₂S, which also plays a role along with C₃S in the later-age strength development.

The early-age strength development of VHESC produced using portland cement is due to the reaction between the accelerating admixture and the hydration products of cement, mainly C₃A and C₂S. For VHESC produced using special cements, early strengths are mainly due to rapid reaction between the cement and mixing water.

20.3—Selection and evaluation

For the production of very high-early-strength concrete (VHESC), materials such as aggregates and cement should be selected based on their local availability. If early strength requirements are not met using a Type I or Type II cement, Type III cement should be used. High-range water-reducing admixtures (HRWRAs) can achieve up to 40 percent water reduction. They allow for the use of workable, low-w/c concrete that sets and develops strength faster and, therefore, should be considered for use in VHESC. Some HRWRAs based on polycarboxylate technology have been found to produce higher early strengths in comparison to conventional HRWRAs based on sulfonated naphthalene and melamines (Collepardi and Valente 2006).

Selection of the correct accelerating admixture is very important to produce VHESC. Accelerating admixtures of different base materials react with different hydration products of the cement. The performance of accelerating admixtures has also been found to be sensitive to different cements in terms of set time and early-age strength. Some accelerators retard the set time of concrete when used at lower dosages, but accelerate the set time when used at higher dosages (for example, sodium and potassium carbonate). Accelerators containing triethanolamine, however, delay the set time used at higher dosages (Ramachandran 1995). Proper evaluation of an accelerator at different dosages is necessary during the trial mixture design process.

Accelerators based on calcium chloride produce very high early strengths, but are generally not used, as they can promote corrosion, alkali-aggregate reaction, increased shrinkage, and lower resistance to sulfate attack. In the field, nonchloride inorganic accelerators such as nitrates and nitrates have shown good performance in terms of high early strengths for air-entrained VHESC. The influence of different accelerators on different cements is discussed in Chapter 7.

Air-entraining admixtures that produce satisfactory results and are compatible with other materials should be used in environments where exposure to cycles of freezing and thawing should be considered.

In case of VHESC, the dosage of a set accelerator is generally higher as compared to its use in conventional concrete. This can reduce the workable life of the concrete significantly. For this reason, realistic transport, placement, and finishing time of the concrete should be calculated and considered when deciding if the set accelerator should be added at the plant or when the truck reaches the jobsite. The timing of addition of the accelerator in trial mixtures should be based on this, and trial batches conducted to simulate the entire concrete operation on the given day of concreting. The early strength of concrete is highly influenced by the temperature of the concrete and ambient temperature. Laboratory trial batches should be run to simulate the time required for mixing, transport, placing, and finishing operations at the jobsite, and early strength should be measured. Trial mixtures should also be carried out at different admixtures dosages at different temperatures. The rate of development of early strength should be monitored using the concrete maturity concept. Maturity correlation relationships should be developed in the laboratory for all the mixtures prior to field application.

If the VHESC is to be produced using special rapid-hardening cement, as discussed in 20.2.1, cement should be selected based on the availability, early strength required, and previous historic data. Trial mixtures should be carried out to simulate concrete operations at the jobsite. When prebagged rapid-repair mortars are selected for use,
recommendations provided by the manufacturer should be followed for using them.

20.4—Proportioning concrete

The proportioning of constituents of very high-early-strength concrete (VHESC) depends on the rate of early strength gain needed, workability, and the time required from mixing to finishing operation. Mixture designs can be proportioned in accordance with ACI 211.1 or other method. The cement contents for VHESC are typically higher than those of conventional concrete to meet the high early strength criteria. The early strength may also be governed by the dosage of the accelerator and the final strength of the w/cm of the concrete.

Alternately, an experience and evaluation approach can be adopted to proportion VHESC mixtures. A given cement content and w/cm should be selected based on prior experience. Aggregates should be proportioned based on their gradations and the mixture designed using the absolute volume method. Air entrainment and an HRWRA should be added to achieve the desired air content and workability. The accelerator should be added to the concrete at the same time it is added to the concrete on the day of production of VHESC. The amount of water in the accelerator should be accounted for and the w/cm accordingly. If retarding or hydration control admixtures are needed, their influence on workability retention and strength development should be evaluated. Depending on the results obtained, suitable adjustments should be made in the mixture proportions, w/cm, and the admixture dosages. Mixtures using special cements should be designed based on historical field data, research data, and successful test placements.

20.5—Effects on fresh and hardening concrete

20.5.1 Workability—The use of a high-range water-reducing admixture (HRWRA) enables high water reduction and produces workable mixtures, even at a low w/cm. The loss of workability of very high-early-strength concrete (VHESC) is faster than for conventional concrete. This is due to the use of high dosages of the accelerator and the use of Type III cement. When using special cements, the loss in workability is extremely fast due to rapid reaction of these cements with water.

20.5.2 Setting time—The initial and final set time of VHESC is less for concrete control, but this depends on the dosage and base material of the accelerator, ambient and concrete temperature, and w/cm. As discussed in Chapter 7, different accelerators react with components of the cement differently, increasing the rate of hydration and accelerating its set.

20.6—Effects on hardened concrete

20.6.1 Early- and later-age strength—Compressive strengths above 2000 psi (13.8 MPa) have been achieved within 4 hours of placement in the field. The early strength development primarily depends on the dosage of the accelerator, cement type, and w/cm. The strength development of very-high-early-strength concrete (VHESC) increases with the increase in the dosage of the accelerator and reduction in the w/cm. The ultimate strength of the VHESC depends on the w/cm of the concrete mixture. Although accelerators increase, the development of early-age strength, the ultimate strength with some accelerators has been observed to slightly decrease when compared with conventional concrete used without accelerator at the same w/cm.

20.6.2 Freezing and thawing and scaling resistance—Very-high-early-strength concrete (VHESC) likely to be exposed to freezing-and-thawing environments should be air entrained. Properly designed air-entrained VHESC that has an adequate spacing factor can achieve very high early strength and is resistant to damage due to freezing and thawing and scaling.

20.7—Quality assurance and batching

As construction time is critical, production of very high-early-strength concrete (VHESC) requires good quality control and proper coordination of construction activities. Trial batches should be run in the laboratory to simulate mixing, transport, and sequence of addition of materials on the day of production. Successful test placements on site should be made. The rate of strength development of cast-in-place concrete is generally higher when compared with that of lab specimens. This is because the larger volume of the cast-in-place concrete results in a greater temperature rise during hydration, which further accelerates strength gain.

Further recommended guidelines include:

a) The surface of the placed concrete should be covered with insulated blankets or burlap to avoid the escape of heat that builds up within the concrete.

b) Thermocouples should be inserted approximately 1 in. (25 mm) from side corners and at approximately 2 in. (50 mm) from the top and bottom of the slab. The maturity of the slab from the thermocouple showing the lowest temperature should be used to govern the maturity of the pavement.

c) Cylinders that are cast at the site should be conditioned to represent the cast-in-place condition; for example, placed in an insulated box or similarly shielded from heat loss.

d) The dosage of the accelerator should be altered according to the concrete and ambient temperature.

Although VHESC is released to service within 4 to 8 hours after its placement, proper curing procedures should be adopted to allow complete hydration of the cement. Proper curing will generally consist of measures to retain the mixing water.

Because the early-age characteristics of the VHESC are important, proper batching procedures should be followed during production. Moisture corrections should be applied properly for each batch and the appropriate dosages of high-range water reducer and air entrainer should be used to achieve the desired workability and air content. The dosage of accelerator should be decided based on the ambient temperatures.
CHAPTER 21—ADMIXTURES FOR PERVIOUS CONCRETE

21.1—Introduction
The term “pervious concrete” describes a low-slump, open-graded material consisting of portland cement, uniform-sized aggregate, little or no fine aggregate, chemical admixtures, and water. The combination of these ingredients can produce hardened concrete with interconnected pores, voids, that allow water to pass through the concrete easily. Refer to ACI 522R for an extensive discussion on previous concrete. This chapter will emphasize admixture types, their selection, and the effect admixtures have on the performance and properties of pervious concrete.

Removing fine aggregate from the concrete mixture may create an interconnected void structure in the hardened concrete; however, such a concrete mixture can be harsh and may create problems on the job site when discharging from the truck and placing. The open void structure could create rapid moisture loss if the w/cm is low, resulting in rapid stiffening of the mixture, a very narrow working window for placement, and low strength and durability of the hardened concrete. The low w/cm and low amount of fines could make it difficult and slow discharging the material from the concrete truck. Contractors have reported issues with a short working time, the need to retemper, and a labor-intensive effort in placing and compacting pervious concrete. In addition, jobsite conditions such as hot weather, low humidity, travel delays, project congestion, and logistics can further complicate placement. Chemical admixtures can play a key role in overcoming these challenges by improving workability, placeability, and the long-term durability of pervious concrete.

21.2—Materials
Chemical admixtures used to produce pervious concrete should meet the requirements of ASTM C494/C494M or ASTM C260/C260M. Commonly used admixtures are:

a) Air-entraining admixtures (Chapter 5)
b) Extended set-control admixtures (ESCs), also known as hydration-controlling admixtures (HCAs) (Chapter 9) and set-retarding admixtures (Chapter 8)
c) Normal water-reducing admixtures, mid-range water-reducing admixtures (MRWRAs), or high-range water-reducing admixtures (HRWRAs) (Chapter 6)
d) Internal curing admixtures

e) Viscosity-modifying admixtures (VMAs) (Chapter 11)
f) Latex admixtures

These materials are often used in various combinations to provide different performance.

21.3—Selection and evaluation
When producing pervious concrete, several factors should be considered when selecting the type and dosage of admixture including:

a) Size of the construction project
b) Time interval from the introduction of cementitious materials and water into the mixer to placement
c) Ambient and concrete temperature
d) Placement methods
e) Skill and experience of the installer

Due to the wide variety of available admixtures, test placements should be performed to determine the exact dosages and interactions of local materials. The expected performance of a given brand, class, or type of admixture can be estimated from one or more of the following sources:

a) Results from jobs where the admixture has been successfully used, preferably with the same materials and under conditions similar to those anticipated on the project
b) Laboratory tests conducted to evaluate the admixture
c) Technical literature and information from the manufacturer of the admixture
d) Field experience from certified pervious craftsman or experienced consultant

21.4—Applications
Pervious concrete is commonly used in areas where there is a desire to reduce the quantity of stormwater runoff, thereby limiting its impact on the environment. Runoff from developed real estate has the potential to pollute surface and groundwater supplies. As land is developed, runoff leaves the site in higher rates and volumes, leading to downstream flooding and stream bank erosion. Pervious concrete pavement reduces the impact of development by reducing or eliminating stormwater runoff rates and protecting water supplies. Pervious concrete has been used in a wide range of applications (ACI 522R).

21.5—Proportioning
The process of developing mixture proportions for pervious concrete is often a series of trial batches developed in the laboratory and then tested in the field to ensure expected performance. In general, the overarching philosophy of mixture proportioning for pervious concrete is to achieve balance between voids, strength, paste content, and workability. ACI 522R provides an extensive discussion on proportioning pervious concrete.

21.6—Effects on fresh and hardening concrete
21.6.1 Setting time—Pervious concrete typically has a low water content and an open void structure. Under these conditions, the cement paste tends to hydrate quickly and the mixture dries out, thereby shortening the available working time required for placement. Hydration-controlling admixtures (HCAs) are used to extend the life of fresh pervious concrete by slowing the rate of hydration and extending the setting time of the paste fraction, allowing the pervious concrete mixture to remain in its plastic state longer (Bury et al. 2006; Kevern 2010). The dosage of the HCA can be modified to achieve the desired level of working time for placement based on ambient temperature and travel time to the job. If placement includes long haul times or hot weather, the amount of HCA may be increased. On some projects, conventional set-retarding admixtures have also been used successfully to extend the setting time and allow the placement of pervious concrete.
21.6.2 Workability—When pervious concrete mixtures are properly proportioned, the results can be a workable mixture that does not require excess compaction. Pervious concrete is produced with \( w/c \text{m} \) in the range of 0.28 to 0.40 with little or no fine aggregate and can be a harsh mixture compared to conventional concrete. Admixtures help lubricate low-slump mixtures and result in faster discharge time from the truck, better flow, and easier placement and compaction. Mid-range water-reducing admixtures (MRWRAs) or high-range water-reducing admixtures (HRWRAs) (Koehler et al. 2009) provide increased cement dispersion resulting in improved workability, especially in low-\( w/c \text{m} \) pervious concrete. Viscosity-modifying admixtures (VMAs) improve workability of pervious concrete without paste drain-down. Paste drain-down is a condition in which too fluid a cement paste in pervious concrete migrates to the bottom of the slab carrying fines from the coarse aggregate and seals it, making the pervious concrete functionally useless. VMA prevents paste drain-down by adding body to the cementitious paste (Bury et al. 2006; Koehler et al. 2009; Kevenr 2010).

21.6.3 Moisture loss—Because of the open void structure, moisture may rapidly evaporate from the mixture, especially in low humidity or windy conditions. Moisture loss can be compounded when proper external curing methods are not used. Reports indicate that internal curing admixtures based on superabsorbent polymers can maintain moisture in pervious concrete and provide additional water for a more complete hydration of the cement (Kevenr and Farney 2012).

21.7—Effects on hardened concrete

21.7.1 Strength and durability—Achieving the desired strength with pervious concrete is somewhat of a challenge because of its inherently high void content, in the range of 15 to 25 percent, which negatively affects strength. Pervious concrete strength is directly related to its density, which is greatly influenced by workability. Durability is a term that includes pervious concrete’s ability to not only carry intended loads, but also to its resistance to raveling. Admixtures can create a strong paste to coarse aggregate bond that increases compressive strength and improves long-term durability by maximizing cement hydration with the available cement and water. Latex admixtures are reported to improve the bond properties of the paste to the aggregates, as well as improve the freezing-and-thawing resistance of pervious concrete.

21.7.2 Freezing-and-thawing resistance—Air-entraining admixtures, while not commonly used in pervious concrete, can be used in environments susceptible to freezing and thawing. No reliable method exists, however, to quantify the entrained air volume in these materials. It may be prudent to include air-entraining admixtures where placement occurs in colder climates (Kevenr et al. 2008).

21.8—Quality assurance and batching

Production of pervious concrete requires higher levels of plant and site quality assurance than conventional concrete. In the initial proportioning process, proper selection of aggregate size, shape, and amounts; paste volume; and admixtures is needed. Quality assurance methods should be in place to assure that the materials used in initial trials are reproduced during production. ACI 522R discusses quality control processes during construction.

Due to the various combinations of admixtures often used in the production of pervious concrete, the sequence in which admixtures are added to the mixture (3.7) can have a significant effect on performance in the fresh and hardened state. The concrete producer, with assistance from admixture manufacturer, should determine the batching order or sequence for incorporating admixtures.

CHAPTER 22—REFERENCES

ACI committee documents and documents published by other organizations are listed first by document number and year of publication followed by authored documents listed alphabetically.

**American Association of State Highway and Transportation Officials (AASHTO)**

AASHTO M 144-14—Standard Specification for Calcium Chloride
AASHTO M 154/M M 154-12—Standard Specification for Air-Entraining Admixtures for Concrete
AASHTO M 194/M 194-13—Standard Specification for Chemical Admixtures for Concrete
AASHTO T 259-02—Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration
AASHTO T 260-97—Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials
AASHTO T 277-15—Standard Method of Test for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration

**American Concrete Institute**

ACI 201.2R-08—Guide to Durable Concrete
ACI 209R-92(08)—Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures
ACI 211.1-91(09)—Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
ACI 211.2-98(04)—Standard Practice for Selecting Proportions for Structural Lightweight Concrete
ACI 213R-14—Guide for Structural Lightweight-Aggregate Concrete
ACI 222R-01(10)—Protection of Metals in Concrete against Corrosion
ACI 223R-10—Guide for the Use of Shrinkage-Compensating Concrete
ACI 229R-13—Report on Controlled Low-Strength Materials
ACI 232.1R-12—Report on the Use of Raw or Processed Natural Pozzolans in Concrete
ACI 232.2R-03—Use of Fly Ash in Concrete
ACI 233R-03(11)—Slag Cement in Concrete and Mortar
ACI 234R-06(12)—Guide for the Use of Silica Fume in Concrete
ACI 237R-07—Self-Consolidating Concrete
ACI 238.1R-08—Report on Measurements of Workability and Rheology of Fresh Concrete
ACI 301-10—Specifications for Structural Concrete
ACI 302.1R-15—Guide to Concrete Floor and Slab Construction
ACI 304R-00(09)—Guide for Measuring, Mixing, Transporting, and Placing Concrete
ACI 304.2R-96(08)—Placing Concrete by Pumping Methods
ACI 305R-10—Guide to Hot Weather Concreting
ACI 306R-10—Guide to Cold Weather Concreting
ACI 308R-01(08)—Guide to Curing Concrete
ACI 309R-05—Guide for Consolidation of Concrete
ACI 311R-05—Guide for Concrete Inspection
ACI 363R-10—Report on High-Strength Concrete
ACI 318-14—Building Code Requirements for Structural Concrete and Commentary
ACI 506R-05—Guide to Shotcrete
ACI 522R-10(11)—Report on Pervious Concrete
ACI 523.1R-06—Guide for Cast-in-Place Low-Density Cellular Concrete
ACI 548.3R-09—Report on Polymer-Modified Concrete
ACI SP-2(07)—Manual of Concrete Inspection

Astm International
Astm C94/C94M-15—Standard Specification for Ready-Mixed Concrete
Astm C138/C138M-14—Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
Astm C173/C173M-14—Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
Astm C231/C231M-14—Standard Test Method for Air Content of Freshly Mixed Concrete by Pressure Method
Astm C260/C260M-10a—Standard Specifications for Air-Entraining Admixtures for Concrete
Astm C457/C457M-12—Standard Practice for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
Astm C494/C494M-15—Standard Specifications for Chemical Admixtures for Concrete
Astm C642-13—Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
Astm C666/C666M-15—Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
Astm C672/C672M-12—Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
Astm C796/C796M-12—Standard Test Method for Foaming Agents for Use in Producing Cellular Concrete Using Foam
Astm C869/C869M-11—Standard Specification for Foaming Agents Used in Making Preformed Foam for Cellular Concrete
Astm C881/C881M-14—Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete
Astm C979/C979M-10—Standard Specification for Pigments for Integrimly Colored Concrete
Astm C1017/C1017M-13—Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete
Astm C1152/C1152M-04(2012)—Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete
Astm C1202-12—Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration
Astm C1218/C1218M-15—Standard Test Method for Water-Soluble Chloride in Mortar and Concrete
Astm C1260-14—Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
Astm C1293-08b(2015)—Standard Test Method of Determination of Length Change of Concrete Due to Alkal-Silica Reaction
Astm C1524-02a(2010)—Standard Test Method for Water-Extractable Chloride in Aggregate (Sokhlet Method)
Astm C1556-11—Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion
Astm C1582/C1582M-11—Standard Specification for Admixtures to Inhibit Chloride-Induced Corrosion of Reinforcing Steel in Concrete
Astm C1585-13—Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes
Astm C1610/C1610M-14—Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique
Astm C1611/C1611M-14—Standard Test Method for Slump Flow of Self-Consolidating Concrete
Astm C1622/C1622M-10—Standard Specification for Cold-Weather Admixture Systems
Astm D98-15—Standard Specification for Calcium Chloride
Astm E329-14—Standard Specification for Agencies Engaged in Construction Inspection, Testing, or Special Inspection

British Standards Institution
Bs 1881-122:2011—Testing Concrete: Method for Determination of Water Absorption
Bs EN 12390-8:909—Testing Hardened Concrete: Depth of Penetration of Water Under Pressure

German Institute for Standardization
Din 1048-5:1991—Testing Concrete: Testing of Hardened Concrete (Specimens Prepared in Mould)

Authored documents
Provided by: www.spic.ir


Berke, N. S.; Hicks, M. C.; and Hoopes, R. J., 1994, “Condition Assessment of Field Structures with Calcium Nitrite,” Concrete Bridges in Aggressive Environments, SP-151, R. E. Weyers, ed., American Concrete Institute, Farmington Hills, MI, pp. 43-72.


Durable Concrete,” *ACI Journal Proceedings*, V. 45, No. 6, June, pp. 469-488.


British Board of Agrément, 2000, Certificate No. 00/3672, First Issue, 8 pp.

British Board of Agrément, 2005, Certificate No. 05/4217, Third Issue, 8 pp.


Fedroff, D., and Frosch, R. J., 2004, “Formwork for Self-Consolidating Concrete,” Concrete International, V. 26, No. 10, Oct., pp. 32-37.


Fournier, B.; Stokes, D.; and Ferro, A., 2003, “Comparative Fielded and Laboratory Investigations on the Use of Supplementary Cementing Materials (SCMs) and Lithium-Based Admixtures to Control Expansion Due to Alkali-Silica Reaction (ASR) in Concrete,” Proceedings of the 6th CANMET/ACI International Conference on Durability of Concrete, SP-212 Supplementary Papers, American Concrete Institute, Farmington Hills, MI, pp. 823-851.


Lieber, W., and Richartz, W., 1972, “Effect of Triethanolamine, Sugar, and Boric Acid on Setting and Hardening of Cements,” Zement-Kalk-Gips, V. 25, No. 9, pp. 43-49. (in German)


Lukas, W., 1981, “Chloride Penetration in Standard Concrete, Water-Reduced Concrete, and Superplasticized Concrete,” Developments in the Use of Superplasticizers, SP-68, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, MI, pp. 253-257.


Mather, B., 1992, “Calcium Chloride in Type V Cement Concrete,” Durability of Concrete, G. M. Idom International Symposium, SP-131, J. Holm and M. Geckel, eds., American Concrete Institute, Farmington Hills, MI, pp. 169-177.


Other Chemical Admixtures in Australian Concretes,”
Seventh CANMET/ACI International Conference on Superplasticizers and Other Chemical Admixtures in Concrete,
SP-217, V. M. Malhotra, ed., American Concrete Institute,

Performance of Australian Commercial Concrete Modified
with Permeability Reducing Admixture,” The 22nd Biennial
of the Concrete Institute of Australia, Melbourne, Australia,
Oct.

Murakami, J., and Tanaka, G., 1969, “Contribution of
Calcium Thiosulfate to the Acceleration of the Hydration
of Portland Cement and Comparison with Other Soluble Inorganic Salts,”
Proceedings of the 5th International Symposium
on the Chemistry of Cement, V. 2, Cement Association
of Japan, Tokyo, Japan, pp. 422-436.

Method of Recycling Returned Concrete Using Extended Life Admixtures,”
Proceedings of Congress of the European
Ready Mixed Concrete Organization (ERMCO), Lisbon,
Portugal.

National Association of Corrosion Engineers, Houston, TX, 279 pp.

Neeley, B. D., 1988, “Evaluation of Concrete Mixtures for
Use in Underwater Repairs,” Technical Report REMR-CS-
18, AD A193 897, U.S. Army Engineer Waterways Experiment
Station, Vicksburg, MS, 130 pp.

of Some Empirical Test Methods,”
Proceeding of the Third International Symposium on Self-Compacting Concrete,
Reykjavik, Iceland, pp. 59-68.

Colloidal Silica and Silicates to Portland Cement Pastes,”
doi: 10.1016/0008-8846(77)90089-8

Neville, A. M., 1995, Properties of Concrete, fourth

Newlon Jr., H. H., 1971, “Comparison of Properties of
Fresh and Hardened Concrete in Bridge Decks,”
Virginia Highway Research Council Report 70-R56, Virginia
Highway Research Council, Charlottesvile, VA, 114 pp.

Nkinamubanzi, C., and Aitchin, P., 2004, “Cement and
Superplasticizer Combinations: Compatibility and Robustness,”
Cement, Concrete and Aggregates, V. 26, No. 2, Dec.,
pp. 102-109. doi: 10.1520/C2A12329

Corrosion Potential of Steel in Concrete and Mortar,”

Nmai, C. K., and McDonnell, D., 2000, “Long-Term Effectiveness of
Corrosion-Inhibiting Admixtures and Implications
on the Design of Durable Reinforced Concrete Structures,”
Proceedings of the PCI/FHWA/FIB International
Symposium on High Performance Concrete, L. S. Johal, ed.,
Precast Concrete Institute, Orlando, FL, pp. 109-124.

Nmai, C. K., and Violetta, B. K., 1996, “The Use of
Flowing Concrete in Congested Areas,”
Concrete International, V. 18, No. 9, Sept., pp. 53-57.

Foaming Agent for CLSM Applications,”
Concrete International, V. 19, No. 4, Apr., pp. 44-47.

Nmai, C. K.; Farrington, S. A.; and Bobrowski, G. S.,
1992, “Organic-Based Corrosion-Inhibiting Admixture for
Reinforced Concrete,”
Concrete International, V. 14, No. 4, Apr., pp. 45-51.

Nmai, C. K.; Schlagbaum, T.; and Violetta, B. K., 1998a,
“A History of Mid-Range Water-Reducing Admixtures,”
Concrete International, V. 20, No. 4, Apr., pp. 45-50.

Nmai, C. K.; Tomita, R.; Fumiaki, H.; and Buffenbarger,
Concrete International, V. 20, No. 4, Apr., pp. 31-37.

Nmai, C. K.; Vojtko, D.; Schaef, S.; Attiogbe, E. K.; and
Frontier in the Battle Against Drying Shrinkage Cracking,”
Concrete International, V. 36, No. 1, Jan., pp. 53-57.

for Durability Tests,”

Ohama, Y., 1984, Polymers Modified Mortars and
Concretes in Concrete Mixtures Handbook: Properties,
Science, and Technology, V. S. Ramachandran, ed.,

Okada, E.; Hisaka, M.; Kazama, Y.; and Hattori, K., 1981,
“Freeze-Thaw Resistance of Superplasticized Concretes,”
Developments in the Use of Superplasticizers, SP-68, American
Concrete Institute, Farmington Hills, MI, pp. 215-232.

Ozyildirim, C., 1991, “Comparison of Air Contents of
Freshly Mixed and Hardened Concrete,”
Cement, Concrete and Aggregates, V. 13, No. 1, pp. 11-17. doi: 10.1520/
CCA10543J

Concrete Construction, V. 49, No. 6, pp. 40-41.

Perenchio, W. F.; Whiting, D. A.; and Kanton, D. L., 1979,
“Water Reduction, Slump Loss and Entrained Air Void
Systems as Influenced by Superplasticizers,”
Superplasticizers in Concrete, SP-62, American Concrete Institute,

Perkins, P., 1986, Repair, Protection and Waterproofing of
Concrete Structures, Elsevier Applied Science Publishers,
301 pp.

Philleo, R. E., 1986, “Freezing and Thawing Resistance of
High Strength Concrete,”
NCHRP Synthesis of Highway Practice, Transportation Research Board, NRC,

Resistance of High-Strength Concrete,”

Poole, J. L., 2007, “Modeling Temperature Sensitivity and
Heat Evolution of Concrete,” PhD dissertation, The University
of Texas at Austin, Austin, TX, 2007.

Portland Cement Association, 2009, “Cement and
cement.org/basics/concretebasics_chemical.asp (accessed
Feb. 4, 2015).


Powers, T. C., 1975, “Freezing Effects in Concrete in Durability of Concrete,” *Durability of Concrete*, SP-47, American Concrete Institute, Farmington Hills, MI, pp. 1-11.


Schutz, R. J., 1978, “Durability of Superplasticized Concrete,” International Symposium on Superplasticizers in Concrete, Ottawa, ON, Canada, May.


Engineering (ICTE 2007), Southwest Jiaotong University, Chengdu, China, July, pp. 4137-4142.


Swamy, R., 1989, “Superplasticizers and Concrete Durability,” Superplasticizers and Other Chemical Admixtures in Concrete, SP-119, American Concrete Institute, Farmington Hills, MI, pp. 361-382.


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