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Materials Selection for Concrete Repair—Guide

Reported by ACI Committee 546

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Materials Selection for Concrete Repair—Guide

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Materials Selection for Concrete Repair—Guide

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This document provides guidance on the selection of materials for concrete repair. An overview of the important properties of repair materials is presented as a guide for making an informed selection of the appropriate repair materials for specific applications and service conditions.

Keywords: cementitious; cracks; epoxy; materials; methacrylate; polymer; polyurethane; repair; surface sealer; silica fume; test methods; waterproofing.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Concrete is inherently a durable material. However, its durability under any given set of exposure conditions varies with concrete mixture proportions; the presence and positioning of reinforcement; and the detailing, placing, finishing, curing, and protection it receives. In service, it may be exposed to adverse environmental conditions resulting in deterioration, reduction of its service life, and the need for concrete repair. With the increasing number and age of concrete structures, frequent deferral of maintenance, and increased public awareness of deterioration and maintenance needs, concrete repair is becoming a priority in design and construction activities.

Due to an expanding concrete repair industry, new materials and repair methods are continuously being introduced to the construction market. At the same time, due to changing environmental building codes and other regulations, many existing, well-proven products are being reformulated into essentially new products that may have limited track records. The user might not always be informed of these changes.

It is often difficult for a specifier to find the appropriate data to systematically evaluate a product for a given repair situation. Often, test data are unavailable or, if available, are either not presented in useful or appropriate terms, making comparison with other competing materials difficult. One example is the use of nonstandard or modified test methods.

ACI Committee 546 is devoted entirely to the subject of concrete repair. Its principal emphasis is on techniques for concrete repair with limited information on selecting repair materials. Although there are many competent repair materials available commercially, even the highest-quality materials do not perform as expected if they are used inappropriately. The physical properties of repair materials are also important to the performance of a concrete repair. This guide is prepared by Committee 546 to aid the user in specifying and executing typical concrete repairs. **ACI 515.2R** provides additional information on protection treatments.

The objective of this guide is to provide guidance for the materials selection for concrete repair, including:

- (a) Identification of common repair materials
- (b) Discussion of relevant material properties
- (c) Lists and discussion of test procedures to determine these properties

- (d) Recommendations of minimum test values or performance levels (where appropriate)
- (e) Discussion of the importance of specific material properties for various repair applications and service environments

1.2—Scope

This guide discusses material selection for several types of concrete repairs, including the following:

- (a) Concrete repairs
- (b) Overlays
- (c) Crack repairs
- (d) Surface-applied sealers and traffic-bearing elastomeric membrane systems
- (e) Anti-carbonation coatings
- (f) Steel corrosion mitigation including reinforcing steel coatings, embedded galvanic anodes, and corrosion inhibitors
- (g) Concrete bonding agents and procedure
- (h) Crystalline pore blockers

1.2.1 Summary tables of test methods and test values—

Tables 4.7a and 4.7b present summaries of available test methods and typical test values, and summaries of material properties for these materials. Table 5.19 presents a selection guide for crack repair material. Tables 6.5a, 6.5b, and 6.5c present summaries of available test methods and typical test values for these materials. Tables 8.5a, 8.5b, and 8.5c present summaries of available test methods and typical test values for surface sealers, anti-carbonation coatings, and traffic-bearing elastomeric coatings.

1.2.2 Special repair and service environments—This guide covers concrete repair materials for common types of concrete repair. Special repair and service environments may require concrete repair materials with enhancement of specific properties. For the repair of environmental or mass-concrete structures, underwater repairs, and other special repair and service environments, refer to the recommendations of other ACI publications (including those of ACI Committees 207, 350, and 546). Refer to industry organizations and material manufacturers for specific guidance in repair material selection.

1.2.3 Appendix A includes a discussion of numerous current industry issues and concerns, including:

- (a) Material test methods and reporting of test data
- (b) Curing of repair materials and manufacturers' reported test results
- (c) Product limitations and warnings
- (d) Standardized industry acceptance
- (e) Repair material bond
- (f) Corrosion reduction
- (g) Structural repairs
- (h) Ongoing developments

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

There are no notations used in this guide.

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology”. Definitions provided herein complement that source.

concrete repair—the removal and restoration of damaged or deteriorated concrete.

electrical resistivity—the resistance of a material to the flow of electrical charge in the presence of a voltage potential between two points.

permeability—the ability of a material to transmit or resist the penetration of water and waterborne chemicals. This definition differs from that in “ACI Concrete Terminology” in that the ability to transmit or resist the penetration of gases is not included.

portland-cement concrete (PCC)—a composition of portland cement, fine and coarse aggregates, and water.

surface sealer—a material applied to the concrete surface to reduce moisture and chemical penetration into the concrete member. Surface sealers may achieve limited penetration into uncracked concrete but are either too brittle (or applied in a coating too thin) to bridge moving cracks or cracks that may form in the concrete after the material application. Surface sealers are differentiated from **sealers**, as defined in “ACI Concrete Terminology,” in that surface sealers may or may not prevent the penetration of gaseous media, be colorless, or be absorbed by the concrete, and commonly are visible on the concrete surface.

traffic-bearing elastomeric coating—a material applied to the concrete surface to greatly reduce moisture and chemical penetration to the concrete member and that is suited for exposure to pedestrian and/or vehicular traffic. Elastomeric coatings have some flexibility, so they are capable of bridging narrow cracks that experience some movement and some cracks that might form in the concrete after the elastomeric coating application.

volume stability—the initial and long-term changes in the linear dimensions or volume of a material after placement.

working time—the elapsed time from completion of mixing until the material becomes too stiff or otherwise unusable.

CHAPTER 3—SELECTION OF CONCRETE REPAIR AND OVERLAY MATERIALS

The success of concrete repairs depends on determining the cause and extent of concrete distress or deterioration and developing a repair strategy to address those problems. Typical steps in a systematic concrete repair operation are as follows:

1. Conduct an assessment to evaluate existing conditions. The scope should be consistent with the perceived condition of the structure and the owner's repair objectives. The assessment should be performed by qualified individuals, documenting and evaluating visible and concealed deterioration, distress, defects, and damage, as well as conditions with potential to cause future deterioration and distress.
2. Determine cause of damage or deterioration necessitating the repair. Examples might be structural damage such as impact or abrasion, design, detailing, or construction

deficiencies; chemical reaction damage such as alkali-aggregate reaction; physical damage related to cycles of freezing and thawing or thermal movements; and corrosion of the reinforcing steel caused by improper placement or carbonation of the concrete or chloride ingress into the concrete to the reinforcing steel.

3. Assess the application and service conditions to which the concrete repair material will be exposed.

4. Determine the repair objectives, including desired service life.

5. Select a repair strategy, including consideration of an appropriate protection system in conjunction with future maintenance, in terms of what is required to preserve or protect the structure and repairs, and what actual maintenance is likely to be available.

6. Assess the loading before, during, and after the proposed repair procedures.

Once the concrete to be repaired is evaluated and the cause of distress established, details of the proposed repair are developed. This includes evaluating and determining the required physical properties of repair materials, followed by the appropriate selection of available repair materials. Selection is usually based on the ability of the material to conform to repair constraints and objectives as defined in this guide, including consideration of cost and availability.

The repair is then implemented, including protective systems if designed as part of the repair. Refer to **ACI 546R**, where these steps are discussed in further detail.

Every repair application places different demands on repair materials such as required strength, durability, permeability, depth, and orientation of application and desired appearance. It is essential to follow the assessment steps in **Section 1.2** to achieve satisfactory results. As overlays have many similar demands to concrete repairs, selection of overlay materials is also included in this chapter.

Repair materials should have suitable properties to meet the demands of the repair application throughout the intended life of the repair. All repair materials have limitations, and the material specifier and user should select the materials with the highest likelihood of long-term performance. Of particular concern can be substrate, ambient, material, and curing temperatures at time of installation, as there are minimum and maximum temperatures for different types of materials, which can vary by application. The reader is also directed to **ACI 318-19(22)**, Table 19.3.1.1, for exposure categories and classes.

Many of the proprietary products for concrete repair that are available commercially are blends of several types of materials. Because these materials are proprietary, a list of their ingredients is usually unavailable to the specifier, except possibly in terms of generic materials. Prior experience with specific products and the results of independent testing of products are useful in evaluating such products. In this regard, many State and Canadian Provincial Departments of Transportation (DOTs) maintain lists of approved proprietary concrete repair materials. These lists provide useful input from the specifier and user of products that have been found satisfactory by those agencies. Because repair

products may be reformulated and their physical properties altered over time, some DOTs periodically update their approval lists based on regular retesting. The American Association of State Highway and Transportation Officials (AASHTO) maintains a Product Evaluation List Management System, APEL (<https://apel.transportation.org>), where the findings of evaluations of new, proprietary, or both new and proprietary engineered transportation products are voluntarily posted.

Compatibility between the properties of concrete repair and overlay materials and those of the intended substrate is an important consideration. For example, in many concrete repair applications, the properties of repair materials, such as the coefficient of thermal expansion and creep, should be similar to those of the substrate. In contrast, the success of many crack repair applications depends on repair materials that have significantly different properties, such as high elasticity and low modulus of elasticity, from that of the substrate, and which will perform better than the base concrete in the service environment. Regardless, it is necessary to identify the repair material properties and the substrate properties before an approach to the repair is determined (**McDonald et al. 2002**). Further discussion on material properties is provided in **Chapter 4**.

3.1—Types of concrete repair and overlays

Based on typical repair thicknesses and common methods for applying these materials, the following sections on concrete repairs and overlays are divided into three categories: 1) deep concrete repairs (including full depth) and overlays; 2) shallow concrete repairs and overlays; and 3) thin overlays. For the purposes of distinguishing repair materials in this guide, deep concrete repairs and overlays are thicker than 1.0 in. (25 mm) and the repair materials include coarse aggregate; shallow concrete repairs and overlays are at least 1/16 (0.06) in. (1.6 mm) thick and less than 1.0 in. (25 mm) thick, and the repair materials include fine aggregate only; and thin overlays are essentially thick coatings less than 1/16 (0.06) in. (1.6 mm) thick.

3.2—Deep concrete repairs and overlays

Deep concrete repairs and overlays, defined for the purposes of this guide as thicker than 1 in. (25 mm), are commonly constructed with repair materials that include fine and coarse aggregates.

3.2.1 Top surface (horizontal) applications—Materials used for deep concrete repairs and overlays in top surface applications include portland-cement concrete (PCC), silica-fume concrete, polymer-modified concrete (PMC), magnesium ammonium-phosphate cement concrete (MAPCC), and polymer concrete.

PCC is the most commonly used material, primarily because of low cost, ease of construction, and adequate compatibility with the substrate concrete. Silica-fume concrete is only moderately more expensive than conventional concrete and is used for protective overlays and concrete repairs in applications where desirable properties, such as increased density and decreased permeability,



Fig. 3.2.1—Placement of concrete overlay. (Courtesy of Euclid Chemical Company.)

are desirable. PMC is used for protective overlays and, less frequently, for concrete repairs due to its higher cost and relatively short time before set. MAPCC is used for concrete repairs in situations where its cost premium is offset by special repair requirements, such as minimum downtime. Polymer concrete is used for concrete repairs and overlays in situations where its cost premium and differing properties from the concrete substrate are offset by special repair requirements, such as minimum downtime or resistance to chemical attack. Figure 3.2.1 shows a concrete overlay placement.

3.2.2 Vertical and overhead applications—For vertical and overhead applications, two primary concerns for repairs that are not formed are adhesion of the repair material to the substrate concrete, and cohesiveness of the repair material during its application and curing to resist the pull of gravity. Where certain vertical and overhead concrete repairs may not commonly be exposed to as aggressive an in-service environment as top surface repairs, some durability properties may be less critical. Refer to [ACI 318-19\(22\)](#), Table 19.3.1.1, for exposure categories and classes.

One distinguishing characteristic of vertical and overhead repairs is the construction method. Common construction methods are form-and-cast, preplaced aggregate, high-velocity placement with pneumatic pressure (shotcrete), low-pressure spray, and hand- or trowel-applied (3.2.2.1 through 3.2.2.4).

3.2.2.1 Form-and-cast repairs—In form-and-cast repairs, the repair area is formed and the repair material placed by either gravity flow (Fig. 3.2.2.1a) or pumping through an opening in the form or a hole in the substrate concrete. The repair material can also be placed by dry packing (Fig. 3.2.2.1b). Materials used for form-and-cast repairs include PCC, silica-fume concrete, PMC, and polymer concrete. Again, PCC is often used—particularly for vertical concrete repairs where less resistance to gravity is necessary—due to low cost, ease of construction, and adequate compatibility with the substrate concrete. PMC is frequently substituted for PCC due to its increased bond strengths. As vertical and overhead repairs are more labor-intensive and frequently have smaller repair quantities, the cost premium for PMC is often not a controlling factor. Because form-and-

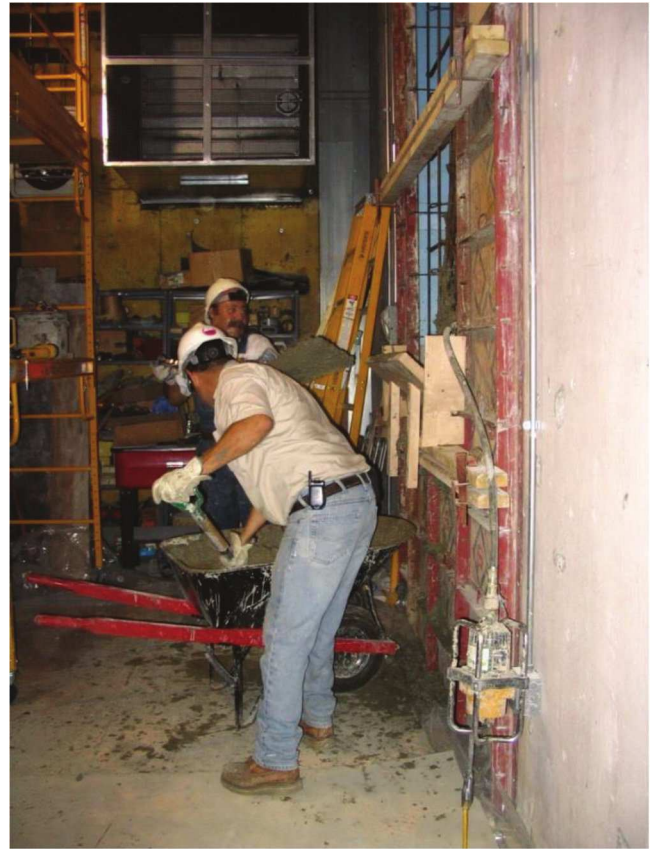


Fig. 3.2.2.1a—Form-and-cast concrete placement in vertical patch. (Courtesy of Wiss, Janney, Elstner Associates, Inc.)



Fig. 3.2.2.1b—Form-and-drypack overhead placement (courtesy of Wiss, Janney, Elstner Associates, Inc.).

cast repairs are self-curing while the forms remain in place, plastic shrinkage and drying shrinkage cracking are normally reduced. PMC or silica-fume concrete is used primarily in special situations where its increased bond strength and durability characteristics offset its additional cost and where differing properties from the concrete substrate are not of concern. PMC can also require that special form surfacing compounds be used, due to its strong adhesion to a wide range of materials. For more information on form-and-pour techniques, refer to [ACI Repair Application Procedure 4](#)

(RAP-4) and ICRI 320.1R; for more information on form-and-pump techniques, refer to [ACI RAP-5](#).

3.2.2.2 Preplaced-aggregate concrete repairs—For the preplaced-aggregate concrete repair procedure, the formed area is filled with coarse aggregate. A cement-sand grout (usually with admixtures) or a resinous material is then injected into the form from the lowest point, resulting in a cohesive concrete or a PMC repair. Preplaced-aggregate concrete contains a higher percentage of coarse aggregate than concrete that is formed and cast. For more information on preplaced aggregate techniques, refer to [ACI RAP-9](#) and ICRI 320.1R.

Because coarse aggregate is preplaced into the repair area and the grout or resin is pumped under pressure, segregation is seldom a problem and virtually all substrate voids should be filled with grout or resin. Drying shrinkage of preplaced-aggregate concrete is typically less than one-half that of conventional concrete because of point-to-point contact of the coarse aggregate. Note that the cement-sand grout may have a relatively high water content to yield a pumpable grout, and this high water content can have an adverse effect on some of the cured material properties, such as permeability and porosity. Preplaced-aggregate and PMC typically have a coefficient of thermal expansion similar to cast-in-place concrete due to the point-to-point contact of the coarse aggregate ([ACI 304.1R](#)).

Preplaced-aggregate repairs require specialized construction skills to install forms with minimal leakage, to place well-consolidated coarse aggregate, and to properly inject the grout or resin. Special equipment is also needed to pump the grout. The repairs also should be consolidated through external vibration.

Applications with prepackaged materials containing a high-range water-reducing admixture (HRWRA) and silica fume made specifically for preplaced-aggregate repairs ([Watson 1996](#)), as well as applications with polymer-modified grout, have proven successful.

3.2.2.3 Shotcrete repairs—Shotcrete is mortar or concrete pneumatically projected at high velocity onto a surface ([ACI 506R](#)). Shotcrete can contain fiber reinforcement and admixtures. Conventional concrete and mortar, silica-fume concrete, and PMC and mortar can all be placed by shotcreting. All the shotcrete ingredients can be combined in a mixer (wet mixture), or the solid ingredients can be combined in a mixer and the water added at the shotcrete nozzle (dry mixture). All materials for site-mixed shotcrete should comply with [ACI 506.2](#). It is more difficult to add and accurately control admixtures with dry-mix shotcrete. Properly placed shotcrete has properties comparable to cast-in-place concrete of similar composition, although the shotcrete operation may reduce the entrained and entrapped air contents. Drying shrinkage and resulting cracking can be a problem with some shotcrete mixtures, largely because of poor sand gradation, too much water, or both, and the absence of aggregate coarser than 1/2 in. (13 mm). Fiber reinforcement or welded-wire reinforcement can be used to help control the cracking. Refer to [ACI 506.1R](#).



Fig. 3.2.2.3—Shotcrete placement. (Courtesy of Wiss, Janney, Elstner Associates, Inc.)

Special equipment is required to apply shotcrete, and the skill of the nozzle operator is critical for a satisfactory application. The shotcreting process generates dust, overspray, and rebound that can disturb adjacent areas and equipment. Rebound should not be incorporated into the repair material. The use of PMC and mortar requires special skill and experience of the nozzle operator, as hardened overspray may reduce bond and special surface preparation is required between successive layers ([ACI 546R](#)). Figure 3.2.2.3 shows a typical shotcrete placement.

Cement-based concrete and mortar are commonly used for shotcrete because of low cost, ease of construction, and adequate compatibility with the substrate concrete. Silica-fume concrete and mortar are also frequently used because of their increased bond strength and cohesiveness compared with cement-based concrete and cement mortar, resulting in increased construction productivity and less rebound waste. Because of the difficulty in mixing, handling, and cleaning, PMC and mortar are not commonly used for shotcrete.

Proprietary cement mortar can also be placed by low-pressure spraying, similar to wet-mix shotcrete, but at a much lower velocity. Refer to [ACI RAP-3](#) and ICRI 320.1R for more information.

3.2.2.4 Hand- and trowel-applied repairs—For trowel-applied repairs, the repair material is applied directly to the repair location with a trowel (or sometimes by hand). Trowel-applied materials are pressed against the substrate to develop intimate contact without voids. These repairs depend primarily on the adhesive bond between the fresh repair material and the substrate concrete for satisfactory placement. Therefore, surface preparation is critical. These repairs do not have the benefit of formwork to support the material until it sets, or pneumatic pressure to increase the application pressure and adhesive bond of the applied material. Coarse aggregate is normally not included in the repair material because it decreases the cohesiveness to the point where the repair material is weaker than the pull of gravity, and the repair material falls out of the repair area before the material can set.

Repair materials include cement mortar, silica-fume mortar, polymer-modified mortar, and polymer mortar. Trowel-applied repairs are used for deep concrete repairs only in unusual circumstances, such as when the concrete repairs are limited in plan area and number or are in relatively inaccessible locations. The absence of coarse aggregate results in some properties that vary significantly from those of the substrate concrete, such as drying shrinkage, coefficient of thermal expansion, and modulus of elasticity. Refer to [ACI RAP-6](#) and [ICRI 320.1R](#) for more information.

3.3—Shallow concrete repairs and overlays

Repair materials for shallow concrete repairs and overlays, defined for the purposes of this guide as at least 1/16 (0.06) in. (1.6 mm) thick and less than 1 in. (25 mm), commonly include fine aggregates only. However, there are some concrete repairs and overlays, which are at least 3/4 in. (19 mm) in thickness, that commonly contain some coarse aggregate. Shallow concrete repairs and overlays are differentiated from deep concrete repairs and overlays in that repair mortars are generally used in shallow repairs. The materials most commonly used are cement mortar, silica-fume mortar, polymer-modified mortar, magnesium-ammonium-phosphate-cement concrete (MAPCC), and polymer mortar.

The properties of repair mortars are less compatible with those of the substrate concrete in comparison to concrete mixtures used in deep repairs. Increased shrinkage and cracking are common problems for shallow concrete repair and overlay materials, which may necessitate further repairs. Polymer repair mortars may have coefficients of thermal expansion sufficiently different from the substrate concrete so that significant thermal stresses may develop between the repair mortar and substrate concrete.

Proper mixing, placing, and curing procedures become more important as the repair thickness decreases. Repair mortars are frequently site-batched, making mixture consistency and quality more difficult to maintain. The experience of the construction worker is important for achieving a satisfactory application. Timely and adequate curing is critical, except that polymer mortar that does not require curing. Where possible, the addition of even small-sized coarse aggregate (1/4 to 3/8 in. [6 to 10 mm]) can be beneficial to the performance of the repair. Figure 3.3 shows a shallow overlay placement.

Cement mortar is sometimes used for shallow concrete repairs and overlays, but it is susceptible to cracking due to the restraint of shrinkage and higher drying shrinkage. Silica-fume mortar and polymer-modified mortar are commonly used because their increased bond and tensile strengths help to offset the effects of anticipated shrinkage. Their bond and cohesiveness before final set also allow these materials to be placed in thicker lifts for overhead and vertical applications, increasing productivity. Polymer mortar is sometimes used, but special attention should be given to mixture proportion and repair details. Cementitious mortars typically require saturated surface-dry (SSD) surface conditions at time of application; this may be a factor in material selec-



Fig. 3.3—Shallow overlay placement. (Courtesy of Wiss, Janney, Elstner Associates, Inc.)

tion. Thermal compatibility between polymer mortar and substrate concrete can result in cracking and debonding, particularly in situations where service temperature may vary widely. In addition, the bond, tensile strength, and durability characteristics make it a reasonable repair option in most thin repair situations. Refer to [ACI 548.1R](#) for additional information on polymer mortars.

3.4—Thin overlays

Thin overlays, defined for the purposes of this guide as less than 1/16 in. (1.6 mm) thick, are applications that place special requirements on the repair materials, such as more severe effects of surface water evaporation and substrate absorption. Thin overlays are intended primarily to address surface defects and roughness. The materials most commonly used are cement mortar, silica-fume mortar, polymer-modified mortar, and polymer mortar. As repair materials become thinner, differential behavior with the substrate concrete becomes accentuated, and enhanced repair material properties such as bond and tensile strengths become more important. Proper application, along with timely and adequate curing, is critical to satisfactory repair performance. Construction workers frequently require special training in mixing and placement of repair materials.

Cement mortar is sometimes used for thin overlays; however, it is frequently desirable to use a material with higher bond and tensile strengths to offset differential behavior with the substrate concrete. Silica-fume mortar, polymer-modified mortar, and polymer mortar are commonly used because of their increased bond and tensile strengths, and improved durability characteristics. The dimensional stability of polymer mortar also improves its performance. As the repair section becomes thinner, a low modulus of elasticity for polymer mortar will reduce the stresses generated by differential thermal movements; bond and tensile strengths of polymer mortar often offset the generated stresses. Cementitious mortars typically require SSD conditions at time of application. This may be a factor in material selection. Thermal compatibility between polymer mortar and substrate concrete can result in cracking and debonding.

particularly in situations where service temperature may vary widely.

3.5—Aggressive environments and exterior applications

In aggressive environments and exterior applications, the repair approach may include coatings for reinforcing steels exposed in concrete repair areas (refer to [Chapter 9](#)), or surface sealers or coatings on the repairs or on the entire member or structure (refer to [Chapters 7 and 8](#)), to improve the structure's overall durability. Cathodic protection, either active or passive, can also be considered for structures in corrosive environments ([ACI 222R](#)). The repair approach should consider the ring anode or halo effect in existing concrete around repairs that were necessitated by corrosion of reinforcement. In chemically aggressive environments or other unusual applications, a surface sealer, coating, or membrane, or an overlay of silica-fume concrete, PMC, or polymer concrete is sometimes used. Refer to [ACI 201.2R](#) for a discussion of various ways to improve concrete durability.

3.6—Typical concrete repair and overlay materials

It is usually difficult to achieve repairs that match the color and texture of the surrounding concrete. If the finished appearance is critical, special measures such as using white cement, tinting the repair mixture, using proprietary materials, or applying a surface treatment should be considered.

The materials most commonly used for concrete repairs and overlays are:

- (a) Portland or blended cement-based concrete
- (b) Portland or blended cement-based, silica-fume concrete, sometimes with fiber reinforcement
- (c) Portland or blended cement-based, PMC
- (d) MAPCC
- (e) Polymer-based concrete (polymer concrete)
- (f) Portland or blended cement-based mortar (cement mortar)
- (g) Portland or blended cement-based, silica-fume mortar, sometimes with fiber reinforcement
- (h) Portland or blended cement-based, polymer-modified mortar
- (i) Magnesium-ammonium-phosphate-cement mortar (MAPCM);
- (j) Polymer-based mortar (polymer mortar)

3.6.1 Portland-cement concrete (PCC)—PCC is composed of portland or blended cement, fine and coarse aggregates, and water. Admixtures are frequently used to entrain air, accelerate or retard hydration, improve workability, reduce mixture water requirements, increase strength, or alter other freshly mixed and hardened properties of concrete. Pozzolanic materials, such as some fly ashes, may be used in conjunction with portland cement for economy or to affect specific properties, such as reduced early heat of hydration, increased later-age strength development, reduced permeability, or increased resistance to alkali-aggregate reaction and sulfate attack.

PCC mixture proportions should be carefully selected to provide the necessary characteristics for the specific appli-

cation, such as workability, density, strength, durability, or resistance to deterioration under the expected exposure conditions ([ACI PRC-211.1](#)). To minimize drying shrinkage, repair concrete should have the lowest possible water content, the smallest paste volume, the largest coarse aggregate size, and the highest coarse aggregate content that are feasible. Shrinkage-reducing admixtures or shrinkage-compensating components may also be considered when proportioning a concrete mixture. Water-cementitious materials ratios (w/cm) typically fall between 0.40 and 0.50. Follow [ACI 201.2R](#), [ACI 301](#), and [ACI 318](#) for recommended maximum w/cm based on conditions. Mixing, transporting, placing, and curing should follow the guidance of [ACI 213R](#), [ACI 304R](#), [ACI 304.1R](#), [ACI 304.2R](#), [ACI 304.6R](#), and [ACI 308R](#).

Advantages: PCC is readily available; generally well understood; economical; has similar properties to the existing concrete substrate; and is relatively easy to produce, place, finish, and cure. Many properties of repair and overlay concrete, such as modulus of elasticity and coefficient of thermal expansion, are typically of similar magnitude to those of the substrate concrete. Generally, concrete mixtures can be proportioned to match the hardened properties of the underlying concrete, making conventional concrete applicable in a wide range of repairs.

Entrained air can be incorporated into the repair concrete to provide resistance to freezing and thawing. The quality of concrete, particularly its permeability and enhanced corrosion protection of embedded reinforcement, is frequently improved by reducing the w/cm to 0.40 or less in conjunction with using an HRWRA. This type of concrete is called low- w/cm concrete.

PCC can be easily placed under water using numerous familiar techniques and precautions to ensure the integrity of the concrete after placement ([ACI 304R](#); [ACI 546.2R](#)). PCC is typically placed under water using a tremie or a pump.

Limitations: PCC should not be used in repairs where the aggressive environment that caused the original concrete to deteriorate has not been eliminated, unless an appropriate design mixture for the exposure condition is used or a reduced service life is acceptable. For example, if the original deterioration was caused by acid attack, aggressive water attack, or abrasion-erosion, repair with conventional concrete may not be successful unless the cause of deterioration is mitigated or some type of protective coating is applied ([ACI 515.2R](#)).

A PCC or mortar repair will usually contract due to plastic and drying shrinkage, cooling, and autogenous volume changes. If this contraction is restrained through bond to a stable substrate, tensile strains develop in the repair material. When these strains exceed the tensile strain capacity of the hardened concrete, cracks develop. This cracking may require further repair or future maintenance because of the possibility of ingress of deleterious materials, loss of bond to substrate, edge spalling of the crack under traffic conditions, or aesthetic objections. Drying shrinkage can be minimized with appropriate concrete mixture proportioning, such as maximizing the size of coarse aggregates compared with the depth of the application. Plastic shrinkage cracking



Fig. 3.6.1—Concrete being placed. (Courtesy of Wiss, Janney, Elstner Associates, Inc.)

can be minimized with timely application of curing materials and environmental controls. Some admixtures, such as accelerating admixtures, may increase the repair material shrinkage and the resulting cracking. While properly proportioned concrete is durable, other repair materials, such as polymer concrete and magnesium-ammonium-phosphate concrete, are more resistant to certain types of chemical attack. Concrete being placed is shown in Fig. 3.6.1.

Curing requirements, as well as the required properties of the repair material, including strength, modulus of elasticity, and limitations on maximum shrinkage strain, if needed, should be addressed by the licensed design professional (LDP) in the repair specifications.

PCC that is mixed, transported, and placed under hot weather conditions, including any combination of high temperature, low humidity, or wind, requires measures to be taken to eliminate or minimize undesirable effects (ACI 305R). There are also special requirements for producing and placing concrete during cold weather conditions (ACI 306R).

Applications: PCC is often used in repairs involving relatively thick sections and large volumes of repair material. Typically, conventional PCC is appropriate for partial- and full-depth repairs and resurfacing overlays where the minimum thickness is greater than 2 in. (50 mm), especially where the overlay extends beyond the reinforcement, or where the repair area is large. Conventional PCC is commonly used for repairs of slabs, walls, columns, piers, and hydraulic structures, as well as for full-depth repairs or overlays on bridge or parking structure decks.

Conventional PCC is particularly suitable for repairs in marine environments because the typically high humidity in such environments minimizes the potential for shrinkage (Troxell et al. 1958).

3.6.1.1 Common PCC chemical admixtures—ACI defines chemical admixtures as a liquid or dispersible powder, used as an ingredient in a cementitious mixture to improve its economy and/or properties in the plastic and/or hardened state.

3.6.1.1.a Accelerating admixtures—Accelerators increase the rate of hydration of hydraulic cement in concrete or mortar, shortening the set time, increasing the rate of strength development, or both. Accelerating admixtures used

in concrete should meet the requirements of ASTM C494/C494M Type C or E.

Advantages: Accelerators are useful for modifying the properties of concrete or mortar to normalize set times in cold weather and increase the rate of early strength development to permit earlier removal of forms and earlier opening of construction (ACI 212.3R). Using accelerators in cold-weather concrete typically is not sufficient to counteract effects of low temperature and should be combined with cold-weather concreting practices (refer to ACI 306R).

Limitations: Accelerating admixtures should not be considered anti-freeze, because at normal dosages, accelerating admixtures lower the freezing point of water in concrete by only 4°F (2°C). Significant lowering of the freezing point of water requires very high dosages of accelerators, which can cause undesirable side effects. One of the major disadvantages of calcium chloride accelerator is that it can cause corrosion of reinforcing steel embedded in the concrete or repair material when in the presence of sufficient moisture and oxygen. Non-chloride accelerators should be used when the potential for corrosion is present.

Applications: Both chloride and non-chloride accelerators are used in concrete or mortar applications in cold weather, or whenever a fast set and strength gain is required.

Standards: Refer to ASTM C494/C494M and ASTM D98.

3.6.1.1.b Set-retarding admixtures—Set-retarding admixtures delay the setting of the cement paste and reduce the rate of hydration in concrete. Retarding action is achieved by the addition of sugar, carbohydrate derivatives, soluble salts and borates, or methanol to the concrete mixture.

Advantages: Set-retarding admixtures are used to decrease slump loss and extend workability, especially in hot weather, to ease placement and finishing of concrete.

Limitations: Set-retarding admixtures generally reduce the strength of concrete at an early age. If excessive quantities of such retarders are used, they can prohibit the setting of the concrete. Results are also dependent on when the retarder is added to the mixture.

Applications: Retarders are often used when placing concrete in hot weather when the normal setting time is shortened, during difficult placement, mass-concrete pours, or when placing concrete that requires a unique finishing technique such as exposed aggregate. Often in exposed aggregate finishing, retarders are applied to concrete surfaces and to the interior face of formwork before placement so that the hardening of the cement on the formwork is delayed. This allows the cement surface to be removed more easily to obtain the desired exposed-aggregate finish.

Standards: Refer to ASTM C494/C494M.

3.6.1.1.c Water-reducing admixtures—Water-reducing admixtures (WRAs) are chemical admixtures that, when added to cementitious materials such as concrete or mortars, release the water entrapped between the cement particles and make it available to increase the workability of the mixture. They are available in both liquid and powder form. WRAs used in prebagged repair materials are typically in powder form and those used for concrete production are typically

in liquid form. WRAs used in cement mortars or concrete should meet the requirements of **ASTM C494/C494M** Type A, D, E, F, or G. Depending on their water-reducing capacity, WRAs can be classified as WRAs (Types A, D, or E) or HRWRAs (Types F or G). For more information on WRAs, refer to **ACI 212.3R**.

Advantages: WRAs are used in cementitious concrete or mortars for three primary reasons: 1) to increase the workability at the same w/cm ; 2) to increase strength by reducing the w/cm at the same workability; or 3) to optimize the cementitious content by keeping the workability and w/cm the same. Typically, a combination of all three benefits is taken during concrete or mortar mixture proportioning.

Increased workability allows the concrete or mortar to be placed easily, especially in confined spaces. Reducing the w/cm allows increasing the strength and durability of the concrete or mortar without compromising workability. Cement optimization allows controlling the heat generated during the heat of hydration of cement, and allows lowering the cost of the cementitious mixture.

Limitations: Adding the correct amount of WRA in cementitious mixtures is important; a dosage rate that is too high can cause problems such as bleeding, segregation, or extension of set time. A dosage rate that is too low can result in reduced workability, which can prevent proper placement of the mixture. Some WRAs can also cause an increase in the air content of the mixture.

Applications: WRAs are used for concrete production in the ready mixed, precast, and dry-cast industry, and in on-site or mobile concrete plants. WRAs are also used in prebagged cementitious mortars or concrete. HRWRAs are an important constituent of self-consolidating concrete (SCC). However, aggregate proportioning and other mixture constituents are also important design considerations for SCC (refer to **ACI 237R**).

Standards: Refer to ASTM C494/C494M.

3.6.1.1.d Corrosion-inhibiting admixtures—Several classifications of corrosion-inhibiting admixtures are available. They can be generally grouped into three types: cathodic, anodic, and ambiotic (or mixed) inhibitors, depending on their area of activity on the corroding steel. Cathodic inhibitors act to prevent the reaction at the cathode. Cathodic inhibitors act indirectly because they do not prevent metal dissolution. Anodic inhibitors reduce the rate of reaction at the anode. They typically react with the corrosion products to form a protective coating on the metal surface. Nitrite-based corrosion inhibitors are one common type of anodic inhibitor. Mixed inhibitors influence both the anodic and the cathodic sites that are claimed to be advantageous in reinforced concrete due to the prominence of microcell corrosion.

Inhibitors are classified by the Strategic Highway Research Program SHRP-S-666 (Al-Qadi et al. 1992) as adsorbed layer formers, oxidizing inhibitors, passivators, conversion layer formers, and scavengers. Adsorbed layer formers are organic inhibitors that strongly adsorb to the metal surface and interfere with the anodic or cathodic reactions in the area of adsorption. Nitrogen is typically the active atom in an adsorbed layer inhibitor acting in a non-acid electrolyte on

steel. Typical compounds of nitrogen used as inhibitors are organic nitrate and amines. Vapor phase inhibitors (VPIs) or volatile corrosion inhibitors (VCIs) are similar to adsorbed layer inhibitors. VPIs are secondary electrolyte layer inhibitors that possess appreciable saturated vapor pressures under atmospheric conditions, thus allowing significant vapor phase transport of the inhibitive substance. Aliphatic and cyclic amines and nitrites with a high vapor pressure typically make up these inhibitors. VPIs/VCIs can be added to cementitious materials as admixtures and be used as surface-applied corrosion inhibitors (SACIs). Oxidizing inhibitors or passivators are another form of barrier inhibitor that act by shifting the electrochemical potential of the corroding metal such that an insoluble oxide or hydroxide forms on the metal surface. Sodium nitrite and chromates are examples of this inhibitor. Another form of passivators is metal soaps that are a form of the basic alkali and oxidation products of oil and that form passivating films on the metal surface. Conversion layer inhibitors form insoluble compounds on metal surfaces without oxidation. In neutral or basic solution, the presence of calcium and magnesium ions inhibits corrosion by the formation of an insoluble calcareous scale on the metal surface. Finally, scavengers act as neutralizing inhibitors by removing concentrations of corrosive materials such as chloride ion.

Passivating inhibitors cause a large anodic shift of the corrosion potential, forcing the metallic surface into the passivation range and are further divided into oxidizing anions and non-oxidizing ion types. Cathodic inhibitors either slow the cathodic reaction itself or selectively precipitate on cathodic areas to increase the surface impedance and limit the diffusion of reducible species to these areas, and are further classified as cathodic poisons and oxygen scavengers. Organic inhibitors can show both anodic and cathodic effects but, as a general rule, affect the entire surface of a corroding metal when present in sufficient concentration. Organic inhibitors are typically designated as film-forming, to protect the metal by forming a hydrophobic film on the metal surface. Precipitation-inducing inhibitors are film-forming compounds that also have a general action over the metal surface, blocking both anodic and cathodic sites indirectly by forming a precipitated deposit on the surface of the metal to provide a protective film. VCIs and VPIs are compounds transported in a closed environment to the site of corrosion by volatilization from a source. On contact with the metal surface, the vapor of VCI salts condenses and is hydrolyzed by moisture to liberate protective ions.

Advantages: Corrosion inhibitors used as admixtures can be precisely controlled for dosage, pretested for compatibility in the material, and once used, are in intimate contact with the steel to be protected. SACIs for hardened concrete are intended to penetrate into the concrete to reduce corrosion activity.

Limitations: The effectiveness of corrosion inhibitors depends on their concentration. The required amount of corrosion inhibitor is a function of the level of corrosion activity. Anodic inhibitors can increase the rate of corrosion in unprotected areas (Al-Qadi et al. 1992), similar to the

haloing effect that is sometimes produced around repairs due to the increase in the cathodic area after repair. Because of this concentration dependency and effects on adjacent areas—that is, areas that have received insufficient concentrations—inhibitors with these properties are sometimes called dangerous, as they may accelerate corrosion.

Most corrosion inhibitors are water-soluble with some inhibitors also being volatile; therefore, the concentration of inhibitor may change with time. The corrosion activity will also change as concrete deterioration occurs, chloride ions ingress, and carbonation occurs that may require a higher concentration of inhibitor than what is within the concrete. Corrosion is also a complex series of electrochemical processes in a changing environment that can produce varying results with inhibitors in field conditions.

No standards exist to specifically address SACIs and VCIs for concrete, with much of the literature presenting differing opinions about their effectiveness.

Applications: Another classification of corrosion inhibitors is in terms of application. Inhibitors are either admixed with the concrete or repair material as an ingredient, or can be applied to hardened concrete surfaces, relying on penetration to reach the reinforcing steel surface.

Standards: **ACI 212.3R** discusses miscellaneous admixtures for concrete, including corrosion-inhibiting admixtures. **ASTM C1582/C1582M** is a specification for admixtures used as corrosion inhibitors. **ASTM G109** is a widely used test method for evaluating the effectiveness of corrosion-inhibiting admixtures, and various modifications have been used for SACI and VCI types.

3.6.1.1.e Lithium-based admixtures—Various lithium compounds (Li_2CO_3 , LiOH , Li_2SO_4) are used in the formulation of set accelerators for calcium-aluminate-cement concrete, and both lithium hydroxide monohydrate ($\text{LiOH} \cdot \text{H}_2\text{O}$) and lithium nitrate (LiNO_3) have been used to control alkali-silica reactivity (ASR) in PCC. Lithium admixtures consist of water-soluble salts and are used in high-alkali concrete containing reactive aggregates to inhibit and control ASR. For an in-depth discussion of the chemistry related to ASR, refer to Federal Highway Administration (FHWA)-HRT-06-133 (Thomas et al. 2007).

The amount of lithium required to suppress expansion depends on the form of lithium, the nature of the reactive aggregate, and the amount of alkali in the concrete. Many studies have shown that the expansion of concrete for a given aggregate depends on the amount of lithium relative to the amount of sodium plus potassium in the mortar or concrete mixture.

Numerous structures have been treated by spraying the surface of the structure with a solution of lithium (both LiNO_3 and LiOH have been used). Very little lithium penetrates below 1 to 2 in. (25 to 50 mm) unless the concrete is heavily cracked. Even in heavily cracked concrete, the lithium concentration decreases with depth, and its ability to suppress ASR is questionable.

Electrochemical impregnation techniques have been used to increase lithium penetration on a number of structures. Significant lithium can penetrate to a depth of at least 3/4 to

1-1/4 in. (19 to 32 mm), and these dosages are theoretically high enough to have a beneficial effect on reducing ASR-induced expansion.

Vacuum impregnation is an alternative to pressure injection and has been used to increase grout penetration into cracked concrete. Numerous structures have been treated with lithium using this technique; however, documentation of the benefits is not sufficient to draw reliable conclusions.

Before treating a structure with lithium-based compounds, an investigation should be conducted to ensure that the primary cause of damage is ASR. Lithium treatment is unlikely to cure any other deterioration processes such as freezing-and-thawing damage, corrosion of embedded steel, or even alkali-carbonate reaction (ACR). Proper diagnosis involves extracting samples for petrographic analysis and other testing in the laboratory. Following treatment, the potential for further expansion and damage due to ASR can still remain.

Lithium treatment will not repair any damage that has already occurred. A protocol for selecting structures that may be suitable for lithium treatment is available from the FHWA HRT-04-113 (Thomas et al. 2004) and FHWA recommendations for lithium to mitigate ASR.

Treating structures with lithium is a technology that is still under development, and recommended protocols for selecting the type of treatment (for example, topical, electrochemical, or vacuum impregnation) or methodologies for performing the treatment do not exist. Electrochemical and vacuum impregnation requires specialized knowledge and equipment, and should be conducted only by an experienced contractor.

3.6.1.1.f Anti-washout admixtures—Anti-washout admixtures (AWAs) are chemical admixtures that bind the free water in the concrete mixture and reduce the loss of fine materials from the concrete mixture into the water during placement of concrete under water.

Advantages: AWAs are often used in concrete mixtures proportioned for underwater placement. The AWA improves the cohesion characteristics of the mixture and typically makes the concrete less sensitive to changes in the w/cm and admixtures. The loss of cement and other fine material from the mixture due to contact with water during placement is reduced, thus improving the in-place concrete properties. The mixtures can be proportioned to be self-consolidating and to flow around reinforcement.

Limitations: Concretes made with AWAs are often more difficult to finish due to reduced bleed water and may exhibit long setting times. Concretes made with AWAs typically are rich in cementitious materials and may therefore require evaluation of thermal stresses when used in large placements. HRWRAs are used to maximize the benefit of the AWA. Compatibility of admixtures, particularly when air-entraining admixtures are used, should be evaluated using trial batches.

Applications: Concretes using AWAs are used for underwater concrete placement. The mixtures can be placed by tremie, pump, or slipform. Applications include concrete repair as well as new construction. AWAs may allow freefall

of concrete mixtures through 2 to 3 ft (0.6 to 0.9 m) of water during placement. Concrete made with AWA is less susceptible to loss of material due to contact with slowly flowing water.

Standards: AWAs should conform to United States Army Corps of Engineers (USACE) CRD-C661. Test method CRD-C61 can be used to measure the loss of cement paste/fines from freshly mixed concrete resulting from contact with water.

3.6.1.2 Other concrete and mortar additives—Materials added to concrete and mortar that are not supplementary cementitious materials and do not fall under the definition of an admixture are contained in this section.

3.6.1.2.a Fiber reinforcement—Fiber reinforcement consists of conventional concrete reinforced with discrete reinforcing fibers. ACI 544.1R identifies four classifications of fiber-reinforced concrete (FRC): steel fiber-reinforced concrete (SFRC); glass fiber-reinforced concrete (GFRC); synthetic fiber-reinforced concrete (SNFRC); and natural fiber-reinforced concrete (NFRC).

Fiber reinforcement of building materials such as brick and adobe has been practiced for thousands of years. Reinforcing concrete with fibers has become an accepted design option where crack control due to plastic, drying, or service-related shrinkage is desired. FRC has been shown to provide significant increases in durability and impact resistance. Using polyolefin fibers to improve the spalling resistance of concrete in fire events by allowing steam ventilation is well documented. Using fibers in combination with conventional steel reinforcement is practiced where both structural strength and improved crack resistance are needed.

FRC is often used for concrete repairs using conventional and shotcrete placement. Though all four types of fibers have been used to produce FRC, SFRC and SNFRC are more applicable to the concrete repair industry, whereas GFRC and NFRC are more applicable to the fabricated building products industry. Information on FRC or shotcrete can be obtained from ACI 544.1R, ACI 544.3R, ACI 544.4R, and ACI 506.1R.

Advantages: Fibers are typically added during concrete production whether plant- or site-mixed. These fibers can be used to provide reinforcement in thin overlays where installation of conventional reinforcing bars is impractical. The addition of fibers can also increase durability, reduce plastic shrinkage cracking, and limit crack widths in repair materials. Areas subject to shock or vibration loading, where plastic shrinkage cracking is a problem or where blast resistance is required, can benefit from the addition of fiber reinforcement.

Limitations: The addition of fibers reduces the slump and can cause workability problems for inexperienced workers. Rust stains may occur at the surface of SFRC due to corrosion of fibers at the surface.

Applications: Reinforced concrete structures are often repaired with FRC repair mortars, FRC, and shotcrete.

Standards: ASTM C1116/C1116M covers the materials, proportions, batching, delivery, and testing of FRC and shotcrete.

3.6.2 Combination materials—The preceding repair materials are often used in combination to enhance important properties for specific applications. As an example, rapid-setting cement is used instead of conventional Type I/II to produce very-high-early-strength polymer-cement concrete. Whereas conventional PMC overlays should be cured 4 to 7 days before being opened to traffic, high-early-strength PMC (PMC-HE or PCM-VE) can be subjected to traffic in less than 1 day. Using PMC-VE reduces down time and inconvenience to motorists; allows for installation at night; provides negligible to very low permeability; and produces high strength, particularly high early strength (Sprinkel and Ozyildirim 1998).

3.6.2.1 Shrinkage-compensating cement concrete—Shrinkage-compensating cement is used in concrete to minimize cracking caused by drying shrinkage. The basic materials and methods are similar to those used to produce high-quality PCC. Consequently, the characteristics of shrinkage-compensating concrete are, in most respects, similar to those of PCC. Proprietary, prepackaged mortar that uses some form of shrinkage-compensating cement or expansive component to counteract potential shrinkage is available and has been used successfully for years. For definitions of expansive cement and expansive component Types G, K, M, and S, refer to ACI PRC-223.

Advantages: Ideally, unrestrained shrinkage-compensating concrete will expand by an amount equal to or slightly greater than the drying shrinkage. Generally, however, reinforcement or external supports result in restraint, which initially causes compressive stresses in the concrete. These stresses are subsequently relieved by drying shrinkage but are of sufficient magnitude to prevent cracking. The joints used to control shrinkage cracking can be reduced or eliminated along with the normal provisions for waterstops and load-transfer mechanisms. Where a watertight condition is essential, however, the elimination of waterstops is not recommended.

Limitations: Although its characteristics are similar to those of PCC, the materials, selection of proportions, placement, and curing should be such that sufficient expansion, compressive stresses, or both, are obtained to compensate for subsequent drying shrinkage. The criteria and practices necessary to ensure that expansion occurs at the time and in the amount required are given in ACI PRC-223. Low curing temperatures can reduce expansion, so water-curing at moderate temperatures for at least 7 days is essential for the development of the designed expansion. Consult with the manufacturer to determine the need for any special cleaning of transit mixer drums to prevent contamination.

Provisions should be made to allow for initial expansion of the material to provide positive strain on the internal steel restraint. Other types of restraint, such as adjacent structural elements, integral abutments, and subgrade friction also provide restraint and produce compression in the concrete. Provisions need to be taken to assure an expansion coefficient higher than that of shrinkage to avoid cracking from drying shrinkage. The forces created during expansion

process could push out walls or fail the forms along the perimeter of the pours.

Applications: Shrinkage-compensating concrete minimizes cracking caused by drying shrinkage in concrete slabs, pavements, bridge decks, and structures. Additionally, shrinkage-compensating concrete can reduce warping tendencies where concrete is exposed to single-face drying and carbonation shrinkage.

Standards: *ASTM C845/C845M* provides standards and limits for expansive hydraulic cement and expansive components, including strength, setting time, and expansion. Mortar and concrete expansion are typically determined in accordance with *ASTM C806* and *ASTM C878/C878M*, respectively. Guidelines for the use of shrinkage-compensating concrete are outlined in *ACI PRC-223*.

3.6.2.2 Rapid-setting cements—Rapid-setting cementitious materials are characterized by faster setting times than conventional cements, as defined by *ASTM C1600/C1600M*. Some may exhibit rapid strength development with compressive strengths exceeding 3000 psi (21 MPa) in 1-1/2 hours.

Advantages: Rapid-setting cements provide accelerated strength development that allows the repair to be placed into service more quickly than conventional repair materials. This advantage is important in repairing highways, bridges, airport runways, and industrial plants because of reduced protection times, lower traffic-control costs, and improved safety. Some rapid-setting cements provide significant reduction in shrinkage and increase durability in sulfate exposures and with reactive aggregates.

Limitations: Although most rapid-setting materials are as durable as normal PCC, some, due to their constituents, may not perform well in a specific service conditions. Rapid-setting cement systems are varied and should be evaluated for suitability in the intended application.

Some rapid-setting materials obtain their strength development, expansive properties, or both, from the formation of ettringite. If the level of expansion is high and the time to attain the maximum levels of expansion is long, strength retrogression may occur. The potential for delayed expansion resulting from insufficient initial curing followed by rewetting should be recognized.

Some rapid-setting materials are gypsum-based and may not have long-term durability in wet environments.

Because some of these materials may contain abnormally high levels of alkali or aluminate to provide expansion, their exposure to sulfates and reactive aggregates should be limited. The specifying engineer should review appropriate application and compatibility issues.

Applications: Rapid-setting cements are especially useful in repair situations where an early return to traffic is required, such as repair of pavements, bridge decks, airport runways, and industrial plants.

Standards: *ASTM C1600/C1600M* covers performance requirements for rapid-hardening hydraulic cements. They are classified as ultra-rapid hardening (URH), very-rapid hardening (VRH), medium-rapid hardening (MRH), or general-rapid hardening (GRH) based on setting time,

compressive strength, and other specific criteria. There are no restrictions on the compositions of the cement or its constituents. Cements are classified based on specific requirements for very early compressive strength development such as time of setting, compressive strength, and other test methods. As mentioned in 3.6.3.2, some rapid-setting cements may not perform well in specific service environments. The standard and optional physical requirements of *ASTM C1600/C1600M* are valuable in determining the suitability of a rapid-setting cement for specific applications. *ASTM C928/C928M* covers packaged, dry, cementitious mortar or concrete materials for rapid repairs to hardened hydraulic-cement concrete pavements and structures. Use caution to check on exposure conditions, such as sulfate exposure and alkali reactivity, that are not covered in the specification. Therefore, additional testing should be performed at anticipated application temperatures to verify if properties not covered in the specification are important for a given project. Advances in the compounding of rapid-setting cements have taken place in recent years.

3.6.2.3 Silica-fume concrete—Silica fume, a by-product of the ferrosilicon industry, is a highly pozzolonic material used to enhance mechanical and durability properties of concrete. Silica-fume concrete is conventional PCC with silica fume and an HRWRA added. Typical silica fume dosage ranges from 5 to 10% replacement of cement by mass.

Advantages: Silica fume is commonly added to concrete to decrease permeability, increase density and strength, and improve quality and performance in a wide range of applications. Silica-fume concrete has properties similar to, but generally stronger than, conventional concrete, including higher bond strength. It also has lower permeability and provides increased protection against corrosion of embedded reinforcement. It is more resistant to attack by some chemicals and to the abrasive action of waterborne solids in hydraulic structures with high flow rates in confined areas (*ACI 234R*).

Silica-fume concrete requires no significant changes from the normal transporting, placing, and consolidating practices associated with conventional concrete, except HRWRAs are required. Further, any retempering of silica-fume-modified concrete should be done with an HRWRA rather than with water.

Limitations: Silica-fume concrete is more cohesive and has less bleed water than conventional concrete. Consequently, it is more difficult to finish and, without proper protection during placement and timely curing, more susceptible to plastic shrinkage cracking than concrete with a moderate *w/cm*. Properly trained or experienced placing and finishing crews, however, have been able to overcome these differences without any significant difficulties (*Holland 1987*).

The potential for cracking of restrained concrete repairs, with and without silica fume, should be recognized. Any variations in concrete materials, concrete mixture proportions, and construction practices that minimize shrinkage or reduce temperature differentials should be considered.

Cracking due to restrained shrinkage or temperature movements may necessitate further repair.

Silica-fume concrete has a gray to black color and may not blend in well with the appearance of the adjacent existing concrete (ACI 234R).

The minimum curing temperature should be 40°F (4°C). Also, wet curing should start as soon as the concrete surface begins to dry (Lerch 1957; Kosmatka 1994; Al-Fadhala and Hover 2001) for a recommended minimum of 7 days.

Applications: The first major applications of silica-fume concrete in the United States were for repair of hydraulic structures subjected to abrasion-erosion damage (Holland and Gutschow 1987). The high strength of silica-fume concrete and the resulting abrasion-erosion resistance offer an economical solution to abrasion-erosion problems, particularly in areas where locally available aggregate may otherwise result in unacceptable concrete for abrasion and erosion resistance.

Silica-fume concrete has been used extensively in overlays on parking structures and bridge decks to reduce the intrusion of chloride ions into the concrete. It is especially suitable for marine environment repair systems due to the reduced permeability of concrete achieved through the use of silica fume.

3.6.2.4 Polymer-modified concrete (PMC)—PMC is a portland or blended cement-based concrete with polymer modifiers added. Typical polymer modifiers include styrene butadiene, acrylic, vinyl acetate-ethylene, styrene acrylic, and epoxy. Generally, the polymer modifier is added at the rate of 10 to 20% by mass of cement. The w/cm for concrete with a latex modifier is normally 0.30 to 0.40, including the water in the latex, and 0.25 to 0.35 for concrete with an epoxy modifier.

Advantages: PMC overlays are often chosen for their long-term performance. Compared with conventional concrete, PMC has increased flexural and bond strength, reduced permeability, and provides increased protection against corrosion of embedded reinforcement (Mindess and Young 1981). Latex-modified concrete overlays installed on severely deteriorated bridge decks after proper surface preparation continue to perform many years after installation. Reports of satisfactory long-term performance on structures of variable initial condition and harsh in-service exposure are common (Virginia Transportation Research Council 2001).

The bonding characteristics of PMC are excellent (Kuhlmann 1990), and PMC typically exhibits low permeability (Kuhlmann 1984).

Limitations: PMC should be placed and cured at 45 to 85°F (7 to 30°C) with special precautions taken when either extreme is reached (ACI 548.1R; ACI 306.1).

PMC is more difficult to place and finish than conventional concrete and has a relatively short working time—approximately 15 to 30 minutes—before the dispersed polymer begins to coalesce. Although it can still be worked after the polymer has begun to coalesce, the beneficial properties of the polymer modification will be significantly reduced. The mixture should never be retempered. The manufacturers'

instructions may not recognize the constructability limitations as described previously (ACI 548.1R).

Because of the short working time, polymer-modified materials should be batched and mixed on-site. When a concrete mixer is used on small repairs, batch sizes should be restricted to quantities that can be placed and finished within the working time. A longer mixing time may result in a marked increase in total air content, which can result in a significant reduction in the compressive strength. Because the manufacturer may or may not add a defoaming agent to the polymer, they should be consulted for the recommended mixing procedures and times. Mobile mixers are frequently used where large quantities of PMC are required. It is recommended that air content tests be performed.

PMC is normally moist-cured for 1 to 2 days, followed by air-drying. While the drying shrinkage of concrete is not increased by the addition of polymers, PMC is more sensitive to plastic shrinkage if curing material is not applied as soon as practical. Concrete modified with styrene butadiene or some epoxies will exhibit color change when exposed to ultraviolet (UV) light (ACI 548.1R; ACI 548.3R). Time for handling and finishing PMC is limited to less than 30 minutes; therefore, mobile volumetric mixers fitted with an additional storage tank for the latex should be used for large applications of latex-modified concrete. When small batches are mixed in drum or mortar mixers, the mixing time should be limited to 3 minutes. Longer mixing times result in an increase in total air content with subsequent reductions in compressive strength. Latex-modified concrete has a tendency for plastic shrinkage cracking during field placement. Special precautions are necessary when the evaporation rate exceeds 0.1 lb/ft²/h (0.5 kg/m²/h) (ACI 308R; ACI 548.4).

The modulus of elasticity is generally lower compared to conventional concrete; therefore, its use in vertical or axially loaded members should be carefully evaluated (Kuhlmann 1990).

Neither polyvinyl acetates nor ethylene vinyl acetates should be used in applications that may be exposed to moisture.

Epoxy emulsions are more expensive than most latexes, and some are susceptible to color change and deterioration from exposure to sunlight. Surface discoloration occurs when the concrete is exposed to UV light. Where such discoloration is not acceptable, acrylic polymers should be used.

Applications: PMC applications include overlays of bridge decks, parking structures, and decks, as well as repair of any concrete surfaces. Styrene butadiene latex is commonly used for repair of bridges, parking decks, and floors. Acrylic latexes are used for floor repair and are particularly suitable in exterior white cement applications where color retention is important.

PMC is most commonly used for overlays and is normally applied in sections ranging from 1.5 to 4 in. (40 to 100 mm) thick for concrete and up to 1.5 in. (40 mm) for mortars. These systems restore lost sections and provide a new high-strength wearing surface that is durable and can be placed into service when it has developed sufficient strength.

cient strength, which is dependent upon the hydration of the cement.

Although mainly used as overlay materials, PMC is also an effective repair material. Typically, PMC repairs are relatively shallow; therefore, mixture proportions similar to those shown in [ACI 548.3R](#) should be considered.

3.6.2.5 Magnesium-ammonium-phosphate-cement concrete—MAPCC is concrete in which magnesium-ammonium-phosphate is substituted for the portland or blended cement. MAPCC is typically classified as ultra-rapid-hardening (Type URH) cement. This classification requires a minimum compressive strength of 3000 psi (21 MPa) at 1.5 hours and a maximum 28-day drying shrinkage of 0.07% ([ASTM C1600/C1600M](#)). Versions with extended set times are also available.

Advantages: MAPCC has increased bond strength, low drying shrinkage, rapid strength gain, and low permeability when compared to PCC ([Popovics and Rajendran 1987](#); [Popovics et al. 1987](#)). Scaling resistance is similar to air-entrained, portland-cement-based concrete materials. When extended with aggregates, abrasion resistance of MAPCC is similar to conventional PCC of similar strength when tested in accordance with [ASTM C672/C672M](#). Neat magnesium phosphate cement naturally has lower abrasion resistance similar to portland-cement mortar of equal strength.

MAPCC is used for specialized applications. The rapid strength gain and volume stability make this repair material an option for fast-turnaround applications and for long, slender repairs. Hot and cold weather formulations are available. Magnesium phosphate mortars (MPMs) are well suited for cold weather applications. MPM and concrete can be placed at temperatures as low as 32°F (0°C). As long as the mixing water is above freezing, the exotherm as the product sets, as well as the ammonia in the product, prevent product freezing. Lower temperatures will slow strength development.

Typically, the drying shrinkage of MAPCC is less than that of other rapid-setting repair materials.

MPMs typically achieve 6000 psi (40 MPa) compressive strength within 48 hours and do not increase much beyond that level. Thin repairs with MPM often have improved performance when compared with portland cement repairs because they generally do not require a moist cure.

Limitations: Because the binder is not based on portland cement, surface preparation, application, and curing requirements are different. MAPCC should not be applied over a carbonated substrate—that is, one with a pH that is no lower than 10—because low bond strength may result. The pH of the substrate should be tested before application. MAPCC hardens rapidly and generates ammonia and large amounts of heat during curing. Aggregates are used for large or deep placements to control the exothermic reaction; however, the aggregates should not contain carbonate minerals to avoid an undesirable chemical reaction with the binder. Placement procedures should avoid trapping ammonia gas within the MAPCC. The only necessary curing is a light application of curing compound in extreme drying conditions, such

as direct sunlight, strong winds, high temperatures, or low humidity. Moist curing is not recommended.

Contamination of MAPCC with other hydraulic cement or contaminated mixing water may result in low strength, rapid stiffening, and poor performance. The specifier and user should consult with the material manufacturer for specific material properties to determine the applicability and use of the material.

Magnesium phosphate concrete and mortar should be extended only with noncalcareous aggregates such as silica, basalt, granite, trap rock, and other hard rocks. Reaction of carbonated surfaces with the early-forming phosphoric acid produces carbon dioxide (CO₂) and weakens the paste-aggregate bond. Because of its acid-base reaction, MAPCC should be used only on well-prepared concrete substrates that have had the carbonation layer removed by mechanical or chemical means. Magnesium phosphate concrete and mortar react chemically with the dust of the fracture, sawing residue, portland cement contamination, or carbonated zone in the concrete and can cause a reduction in bond strength at the bond interface.

Careful attention should be paid to surface preparation and drying times of MAPCC if impermeable membranes are to be applied over it. The MAPCC and membrane manufacturers should be contacted for recommendations.

Because of the short time between initial and final setting times, MAPCC is generally not hard troweled.

The field technician does not have the flexibility of varying the water content and, therefore, MAPCC cannot be placed in a dry-pack consistency. The mixing water typically has a tolerance of only ±10%. Any variation of the water content from that specified by the manufacturer reduces both the strength and the durability of the MAPCC mortar.

The neat or extended MPM develops a very rapid exothermic reaction that can produce relatively high temperatures. Typically, the mortar should not be placed at temperatures above 80°F (27°C) or in the sunlight within the temperature ranges of 60 to 80°F (15 to 27°C). However, hot and cold weather formulas are available and may have different temperature ranges. The manufacturer should be consulted for temperature ranges and when placing the material in thickness greater than 4 in. (100 mm) or in insulated cavities where the generated heat cannot escape. Extending the mixture with aggregates or using cool water can slow down the exothermic reaction.

As it hardens, MAPCC quickly produces high strength and a high modulus of elasticity. Therefore, MAPCC lacks the flexibility and toughness that is typically found with organic-modified mortars and is susceptible to fracturing from impact loads.

With the normal setting formulations of MAPCC, high heat peaks are encountered. With sustained exposure to temperatures exceeding 180°F (80°C) in service, strength reductions can develop, but its compressive strength can be expected to exceed that of normal concrete.

Applications: Repair applications are the most common use of MAPCCs and are cost-effective for most repairs

where a short downtime is important. Common uses are in highway, bridge deck, airport, tunnel, and industrial repairs.

Repairs in a cold-weather environment are important applications. Due to the exothermic nature of the reaction, heating the materials and the substrates is not typically necessary unless the temperature is below 32°F (0°C). Magnesium phosphate concrete and mortar is useful for cold weather embedments and anchoring because of its high bond strength and low shrinkage rate.

3.6.2.6 Polymer concrete—Polymer concrete is one in which an organic polymer serves as the binder. Polymers typically used include epoxy, polyester, furan, vinyl ester, or methyl methacrylate. Portland cement, however, is sometimes used as a filler (ACI 548.1R).

Advantages: Polymer concrete may have low shrinkage as it cures, enhanced bond strength to the substrate concrete, high tensile and flexural strength, low permeability, increased protection against corrosion of embedded steel, and improved resistance to chemical attack (ACI 548.1R), when compared to PCC. It also sets quickly, reducing the down time of the repair area. Because of the rapid setting time, however, it should be batched on-site (Concrete Society 1976).

Polymer concrete can provide a fast-curing, high-strength repair material that is suitable for repair of concrete structures. Polymer concrete is mixed, placed, and consolidated in a manner that is similar to conventional PCC. With some formulations, external vibration is required.

Limitations: The cure time of polymer concrete is directly related to the polymer type and other agents used, concrete substrate temperature, air temperature, and temperature attained by the mixed polymer. While polymer concrete generally sets much more quickly than portland-cement-based concrete, low temperatures or an inappropriate polymer selection may significantly increase the set time. Conversely, high temperatures may reduce the working time below acceptable levels.

Polymer concrete has a significantly higher coefficient of thermal expansion than the substrate concrete, and in situations where the temperature of the service environment is not controlled, the aggregates in the polymer concrete mixture should be carefully graded and proportioned to minimize the distance between the aggregate particles, decreasing the coefficient of thermal expansion (Sprinkel 1983); preplacing the aggregates results in tightly packed aggregate. It is desirable to place polymer concrete near the midrange of service temperatures to reduce cracking and internal stress caused by long-term thermal stress cycles. In many instances, however, some cracking should be anticipated, and further repair may be needed.

Polymer concrete can also have a modulus of elasticity significantly different from the substrate concrete. Many polymer concretes have a lower modulus of elasticity that can be beneficial in reducing stresses that develop from other differences in the material properties, particularly the coefficients of thermal expansion. This, however, may also make this material inappropriate for structural repairs.

Polymer concrete is susceptible to deformation and loss of mechanical properties when heated. Its mechanical properties begin to change as service temperatures approach or exceed its heat deflection temperature (HDT). Although the HDT varies for each formulation, for those systems used in concrete construction, it generally ranges from 60 to 160°F (16 to 71°C). To maintain the reported mechanical properties, the service temperature needs to be 15 to 20°F (–9 to –6°C) below the HDT.

Polymers exposed to fire or some solvents may soften or lose all mechanical properties, depending upon exposure durations and/or intensity.

General construction workers usually are not experienced in working with polymer concrete and will require special training. Moisture in the aggregates or on the concrete surface adversely affects polymer concrete. Special clean-up solvents are necessary; these solvents may be hazardous materials that require special disposal procedures. Special safety equipment and precautions may be necessary due to fumes and flammability of some materials. Polymer concrete usually does not blend in with the appearance of the adjacent existing concrete (ACI 548.1R).

Because the properties of polymer concrete are significantly different from those of the substrate concrete, and because polymer concrete has higher material and installation costs, it is commonly used only for repairs with unusual requirements or in demanding environments where the enhanced properties of polymer concrete are desired.

Organic solvents are required to clean equipment when using polyesters and some epoxies. Manufacturers should be consulted before using proprietary materials to address the issue of volatile organic compound (VOC) restrictions. Epoxy materials are also sensitizers capable of causing allergic reactions and other health hazards. The disposal of epoxy materials that are unreacted may also be classified as hazardous waste in some areas and should therefore be done in accordance with local ordinances.

Rapid curing generally means less time for placing and finishing operations. Working times for these materials are variable and, depending on ambient temperatures, may range from less than 15 minutes to more than 1 hour. Ambient and concrete temperatures may affect polymer viscosity, cure time, or performance.

Shrinkage characteristics of polymer concrete should be closely evaluated so that unnecessary shrinkage cracking is avoided.

The modulus of elasticity of polymer concrete is lower than that of conventional concrete, especially at higher temperatures. Its use in load-carrying members should be carefully considered.

Only a limited number of polymer systems are appropriate for repair of wet, damp, or moist concrete surfaces. The aggregates used in polymer concrete should be dry to obtain the highest strengths and ensure the integrity of the concrete or mortar.

High temperatures can adversely affect the physical properties of certain polymer concrete formulations. Service temperatures should be evaluated before selecting

polymer concrete systems for such use. Epoxy systems may burn in fires where temperatures exceed 450°F (230°C) and can soften at lower temperatures. Users of polymer concrete should consider its lack of fire resistance.

Conventional PCC generally does not bond to cured polymer concrete unless the aggregate is exposed and free of any polymer.

Applications: Polymer concrete repair materials are designed for the repair of a broad variety of conditions that allow closing of a repair area for only a few hours. They are not limited to that use, however, and can be formulated for a wide variety of applications, provided consideration is given to the modulus, creep, thermal, and other properties of a specific product.

Polymer concrete is used in several types of applications—fast-curing, high-strength repair of structures, and thin 0.1 to 0.75 in. (3 to 19 mm) overlays for floors and bridge decks.

Polymer mortars have been used in a variety of repairs where only thin sections, such as overlays, are required. Polymers with high elongation and low modulus of elasticity are particularly suited for bridge overlays.

Polymer concrete overlays are especially well suited for use in areas where concrete is subject to chemical attack.

3.6.3 Mortars

3.6.3.1 Cement mortars and grouts—Cement mortars and grouts generally consists of portland cement, fine aggregate, and water, and may contain other ingredients such as admixtures. Cement mortars and grouts are frequently mixed in small batches at the site; therefore, it may be difficult to maintain uniform characteristics.

Advantages: The advantages of cement mortars and grouts are similar to those of conventional concrete, except that cement mortars and grouts can be placed in thinner sections. A wide variety of prepackaged mortars are available. They are particularly appropriate for small repairs. Cement mortars and grouts are economical, readily available, easy to install, and closely compatible with concrete. Admixtures can modify cement mortars grouts to meet specific job requirements. Shrinkage-reducing admixtures and expansive components are available to minimize shrinkage effects. Non-shrink grouts are also available.

Limitations: Because of the higher water volume, higher cement content, higher paste-aggregate ratio, and absence of coarse aggregate, cement mortars and grout shrink more than concrete, often resulting in more cracking, and further repair may be needed. WRAs, expansive agents, and other modifiers are sometimes used to reduce shrinkage. The coefficient of thermal expansion is dependent on aggregate content, type, and size, and on the cement content; therefore, some differences in thermal properties between mortars and concrete are likely (Neville 1996).

Proper air entrainment is often required to provide adequate resistance to freezing and thawing as well as scale resistance.

Applications: Ready mixed cement mortars and grouts should not be used in many situations when thin repair sections are required. These applications should be reviewed when installed in the path of vehicular traffic that is subject

to repetitive loading. Because field conditions affect the development of the performance of cement mortars and grouts, testing for relevant properties should be performed to closely simulate the application conditions. Typical applications of hydraulic-cement grout may vary from grout slurries for bonding old concrete to new concrete, to filling of large dormant cracks, or to filling of voids around or under a concrete structure. Non-shrink cement grouts can be used to repair spalled or honeycombed concrete or to install anchor bolts in hardened concrete but should be used in accordance with the manufacturer's instructions. Cement mortars and grouts can be used for repairs by injection, but only where the width of the opening is sufficient to accept the solid particles suspended in the grout. The minimum crack width at the point of introduction should be approximately 1/4 in. (6 mm).

3.6.3.2 Prepackaged repair mortars—Prepackaged repair mortars are also commercially available. Hydraulic cement and other ingredients, including fine aggregate, dry admixtures, and, frequently, proprietary ingredients, are blended in a production plant and then packaged, commonly into several sizes of containers.

Advantages: Prepackaged materials may offer more consistent and predictable work-site performance. Refer to ACI 546.4R for more information. The advantages of proprietary repair materials are convenience of use and the broad range of products with different physical and mechanical properties to meet different conditions, such as partial-depth repairs on vertical and overhead surfaces without the need of forms as well as form-and-pour applications. They often have faster set times and shorter cure times when compared with conventional concrete and mortar. They are suitable for performance-based requirements, as the composition typically is formulated to achieve published values. The preblended materials used in proprietary mortars are convenient for small-quantity placements where the proportioning of conventional mortars is inconvenient, difficult to disperse, or too complex for field conditions such as the quantity of material used, rapid hardening, or accessibility.

Prepackaged materials provide better mixture and quality control at the work site as most commonly only water is added at the work site.

During production, most manufacturers inspect and test their materials to confirm that the material meets their product specifications before the material leaves the plant. Some manufacturers are certified by organizations such as International Organizations for Standards (ISO) that monitor quality control, which means that their production processes and procedures are documented and consistent with this documentation. Note, however, that certification indicates a product is produced consistently, but does not guarantee product performance.

Mixture proportions, often including admixtures or proprietary ingredients, are designed to meet specific needs, such as approval for contact with potable water (NSF certification), resistance to freezing and thawing, fast set, abrasion resistance, and low shrinkage.

Performance test results are usually available from the manufacturers. Product data sheet information provides benchmarks for the applicator and specifier to compare with on-site testing; however, differences in test methods may create difficulties comparing properties between materials. Modified test procedures can also produce misleading performance expectations.

Certain mixtures can be extended with coarse aggregate per manufacturers' recommendations to create concrete for repairing deeper sections. The extended mixtures will have properties more similar to concrete rather than mortar.

Limitations: Proprietary repair mortars may have different mechanical properties than the concrete being repaired. In addition, the substrate concrete has likely already experienced most of its shrinkage and property development. Because proprietary mortars may be cement-rich and use a complex blend of modifiers, they can have a propensity for high shrinkage compared with conventional concrete. Shrinkage characteristics can be provided by the material manufacturer. Although there are no industry standards specifying bond strength of these mortars, [ICRI 210.3R](#) or [ASTM C1583/C1583M](#) tensile bond testing is appropriate for evaluating in-place bond. Prepackaged materials have a limited shelf life and generally should not be used after the expiration of this limit.

Applications: Some proprietary mortars are recommended for repairs as thin as 1/8 in. (3 mm). Thin mortar applications should use special products developed for this purpose, especially when installed in the path of vehicular traffic or subjected to repetitive loadings. Testing should be performed under actual field conditions to ensure the satisfactory performance of the material and the installation.

3.6.3.3 Silica-fume mortar—Silica-fume mortar is cement mortar with silica fume added. Silica fume increases the bond strength and cohesiveness of mortar. Silica-fume mortar also has increased compressive and tensile strength, reduced permeability, increased electrical resistivity characteristics, and is also more resistant to chemical attack.

Advantages: The potential advantages outlined in 3.6.3.2 resulting from the use of prepackaged materials apply, plus the benefits associated with the incorporation of silica fume into a repair mortar.

The initial commercial interest in silica fume was for increased chemical resistance of concrete. Silica fume is commonly added to concrete to decrease permeability, increase density and strength, and improve quality and performance in a wide range of applications.

To achieve a maximum improvement in strength and durability, silica-fume concrete should contain WRA, HRWRA, or both. Refer to [ACI 234R](#) for more information.

Limitations: Again, the absence of coarse aggregate causes increased shrinkage and greater tendency to crack. Typically, as silica fume dosage increases, the concrete becomes more cohesive, is more susceptible to plastic shrinkage cracking, and adds significant cost to the repair material. Silica-fume concrete has little or no bleed water, which makes it difficult to provide a steel-troweled finish. Properly trained or experienced placing and finishing crews,

however, have been able to overcome these differences without any significant difficulties ([Holland 1987](#)).

Site-added silica fume may be difficult to adequately disperse.

The minimum curing temperature should be 40°F (4°C). Also, wet-curing should start as soon as the concrete surface begins to dry ([Lerch 1957](#); [Kosmatka 1994](#); [Al-Fadhala and Hover 2001](#)) for a recommended minimum of 7 days.

Applications: The first major applications of silica-fume concrete in the United States were for repair of hydraulic structures subjected to abrasion-erosion damage ([Holland and Gutschow 1987](#)). The high strength of silica-fume concrete and the resulting abrasion-erosion resistance offer an economical solution to abrasion-erosion problems, particularly in areas where locally available aggregate may otherwise result in unacceptable concrete for abrasion and erosion resistance.

Silica-fume mortar has been used extensively in overlays on parking structures and bridge decks to reduce the intrusion of chloride ions into the concrete. It is especially suitable for marine environment repair systems due to the reduced permeability of concrete achieved through the use of silica fume.

3.6.3.4 Polymer-modified mortar—Polymer-modified mortar consists of cement mortar with a polymer modifier added.

Prepackaged repair mortars containing a dry polymer are widely used. The potential advantages of prepackaged materials are reviewed in 3.6.3.2.

Polymer may also be introduced through a second component as a liquid dispersion. This liquid, which contains polymer, water, and usually other additives, may be proportioned such that a specified volume of dispersion is mixed with a bag of prepackaged repair mortar to produce the repair material.

Advantages: Compared with cement mortar, polymer-modified mortar has increased bond strength and cohesiveness, improved resistance to freezing and thawing, reduced permeability, increased electrical resistivity, and improved resistance to chemical attack. Advantages of polymer-modified mortar will be similar to those listed for PMC (3.6.2.6).

Limitations: As with any mortar, increased shrinkage and cracking should be expected because of the absence of coarse aggregate and higher water and cement contents. Limitations of polymer-modified mortar will be similar to those listed for PMC (3.6.2.6).

Applications: Applications of polymer-modified mortar will be similar to those of PMC (3.6.2.6).

3.6.3.5 Magnesium-ammonium-phosphate-cement mortar—MAPCM is mortar in which magnesium-ammonium-phosphate cement is used in place of portland cement, usually for specialized repairs such as those requiring rapid strength development, low shrinkage, application in below-freezing conditions, or very high bond strength. Refer to 3.6.2.5 for further discussion of its use.

3.6.3.6 Polymer mortar—Polymer mortar consists of a polymer binder and fine aggregate. It provides greater volume stability; relatively high compressive, tensile,

and bond strengths; increased resistance to freezing-and-thawing distress; lower permeability; higher electrical resistivity; and improved chemical resistance characteristics when compared to portland-cement mortar. It also sets quickly, allowing the repair area to be returned to service in a short time.

As in the case of polymer concrete, the curing time of polymer mortar is directly related to the polymer and other agents used, as well as the concrete substrate temperature, air temperature, and temperature attained by the mixed polymer. While polymer mortar generally sets much more quickly than portland-cement mortar, low temperatures or the selection of a polymer not intended for the specific repair application may significantly increase the set time.

The coefficient of thermal expansion and modulus of elasticity of polymer mortars can vary significantly from those of the substrate concrete. Differential strains between the repair mortar and substrate concrete, due to high exothermic reactions of some polymer compositions and differences in the coefficients of thermal expansion and moduli of elasticity, can cause cracking and even debonding of repairs (ACI 548.5R). Such cracking and debonding of repairs may require further repair.

Polymers used in polymer mortar soften when heated, such as when exposed to fire, and harden when cooled. Their mechanical properties change significantly beyond their HDT. Although the HDT is different for each formulation, for those systems used in concrete construction, it generally ranges from 60 to 160°F (16 to 71°C). The polymer formulation may require adjustment to achieve proper curing at higher temperature.

Concrete construction workers are often inexperienced working with polymer mortar and will require special training. Moisture in the aggregate or on the substrate concrete surface adversely affects most polymer mortars. Special cleanup solvents are necessary. Special safety equipment and precautions may be necessary due to fumes and flammability of some materials. Polymer mortar usually does not blend in with the appearance of the adjacent existing concrete.

Polymer mortars are ideally suited for thin repairs and overlays less than 3/4 in. (20 mm).

Advantages: Advantages of polymer mortar will be similar to those listed for polymer concrete. Refer to 3.6.2.6.

Epoxy mortars shrink less than polyester or acrylic mortars. Shrinkage of polyester and acrylic mortars can be reduced by using an optimum aggregate loading. The aggregate grading and the mixture proportions should be available from the polymer formulator.

Limitations: Limitations of polymer mortar will be similar to those listed for polymer concrete. Refer to 3.6.2.6.

Applications: A wide variety of prepackaged polymer mortars are available that can be used as mortars or added to selected blends of aggregates. Depending on the specific use, mortars may contain variable aggregate gradations intended to impart unique surface properties or aesthetic effects to the structure being repaired. Polymer mortars that are trowelable, specifically intended for overhead or vertical applica-

tions, or both, are also available. Applications of polymer mortar will be similar to those listed for polymer concrete. Refer to 3.6.2.6.

CHAPTER 4—CONCRETE REPAIR AND OVERLAY MATERIAL PROPERTIES

Compatibility between the properties of concrete replacement and overlay materials and the properties of the intended substrate is an important consideration. This chapter discusses properties of concrete repair and overlay materials, and test methods used to evaluate them. Some test methods are not specifically applicable for certain repair or overlay materials, or repair or overlay installations, but are useful for comparison. Because descriptions of the various test methods are brief, referenced standards should be reviewed for details. Material manufacturers should provide test data based on ASTM standards and other standardized test methods. ACI 364.3R and ICRI 320.3R describe many relevant properties and appropriate modifications to standardized test methods suitable for cementitious repair materials. Refer to Appendix A for further discussion regarding modifications to standard test methods.

Most test methods cited in this guide are performed under laboratory conditions at room temperature, so reported properties may not reflect the actual properties of the repair materials under actual service conditions. In addition, many properties of repair materials, overlay materials, and the existing concrete are time dependent. In cases where material properties are specified, the corresponding age of the materials should be noted. A conclusion from Alberta Transportation's 1987 concrete repair testing program was that the durability of concrete repair materials correlated better with long-term physical properties—for example, 1 year or more after placement—rather than shorter-term physical properties (24-hour and 28-day properties) (Gurjar 1987).

4.1—Volume stability

Volume stability properties affect compatibility of the concrete repair material with the substrate concrete. Substrate concrete is usually relatively stable, with minimal residual creep and shrinkage deformations. The substrate concrete, however, may experience some volume instability for various reasons, including thermal expansion and contraction from seasonal environmental changes. It is desirable for any shrinkage or expansion of the repair material to occur before the repair material has reached its final set, while creep is high. If this is not possible with some repair materials, consideration should be given to accommodating differential movements in some manner in the repair design, such as use of control joints, curing, avoidance of reentrant corners, avoidance of high length-to-width ratio configurations, or treatment of anticipated cracks.

Most cementitious materials undergo early shrinkage within the first few hours to days after application. Non-cementitious materials, such as those with polymeric binders, tend to be more stable with little or no shrinkage after hardening. These materials are more susceptible to greater volume changes due to temperature variations.

Significant changes in repair material volume can cause high horizontal shear stresses at the interface, debonding from the substrate concrete, and cracking of the concrete repair material. Stresses created in the concrete repair material by restrained contraction and expansion may be reduced by using repair materials with a lower modulus of elasticity or a higher rate of creep. Expansion of the concrete repair material may be resisted by providing restraint or confinement, such as by keying it into the substrate concrete. Cracking of the concrete repair material to relieve restrained shrinkage should be anticipated, and further repairs may be needed.

Six test methods are used to evaluate volume stability of concrete, mortar, and cementitious materials:

1. **ASTM C157/C157M**
2. **ASTM C157/C157M**, as modified by **ICRI 320.3R**
3. **ASTM C596**
4. **ASTM C806**
5. **ASTM C827/C827M**
6. **ASTM C1581/C1581M**

ASTM C157/C157M, ASTM C596, and ASTM C806 are test methods that involve monitoring the length of test specimens over time under different curing conditions. A restraining cage with an embedded steel rod is used in ASTM C806 to restrain the specimen expansion. ASTM C827/C827M is a test method that involves monitoring the height of cylindrical test specimens until the specimens harden. ASTM C1581/C1581M is a test procedure that involves measuring the strains and observing cracking in donut-shaped specimens with inner steel rings. The primary use of these test methods is to provide a relative comparison of various materials when tested in the same fashion. Actual shrinkage experienced in the field will likely differ from shrinkage reported from tests. However, laboratory test conditions sometimes yield higher shrinkage results than those that occur in the field.

4.1.1 ASTM C157/C157M—The curing and comparator reading regimen in this test method is not applicable for concrete repair mortars and concretes. The test specimens are approximately 11-1/4 in. (285 mm) long and vary in cross section from 1 in. (25 mm) square for mortar specimens to 3 or 4 in. (75 or 100 mm) square for concrete specimens. Initially, the test specimens are stored in a moist room for 24 hours, demolded, and placed in lime-saturated water for a minimum of 15 minutes for mortar specimens and 30 minutes for concrete specimens. Initial length comparator measurements are taken. The specimens are stored in lime-saturated water until they have reached an age of 28 days, when another set of length comparator measurements are made. After these measurements, the specimens are stored in either lime-saturated water or in a drying room, and length comparator measurements are taken at 4, 7, 14, and 28 days (drying room storage only), and 8, 16, 32, and 64 weeks, including the initial 28-day curing period. The length change, in percent, at any age is calculated. Typical shrinkage strains range from 0.02% expansion to -0.12% shrinkage. The length comparator setup is shown in Fig. 4.1.1.

Neither curing regimen is representative of field conditions for most concrete repair mortars because the initial

length-comparator measurement is made at 24 hours, neglecting volume changes that occur within the first 24 hours; extensive wet curing is used, and the specimens are not restrained. In field conditions, bonding concrete repair materials to the substrate concrete provides restraint to shrinkage and an increased exposed surface area, such as shallow or long slender repair geometries, can significantly increase shrinkage.

When testing shrinkage-compensating mortars, unrealistic curing conditions and inappropriate comparator reading schedules could lead to misleadingly low values of drying shrinkage. It is critical that the demolding time, curing conditions, and comparator reading schedule are understood when interpreting test results. For example, if the initial measurement is recorded while the material is still expanding, the ultimate drying shrinkage appears less than it actually is; the net length change (expansion less shrinkage) during the test, therefore, should be used as the value for drying shrinkage.

The specimen size has a significant effect on shrinkage results. Different-sized specimens have different surface-to-volume ratios, which will affect the rate of shrinkage (Hansen and Mattock 1966). A 1 in. (25 mm) square specimen shrinks more quickly than 3 or 4 in. (75 or 100 mm) square specimens. If larger specimens are used, it may be



Fig. 4.1.1—Length comparator with standard calibrating rod (ASTM C157/C157M) (Photo courtesy of BASI Construction Chemicals, LLC.)

appropriate to consider shrinkage at 16 weeks instead of 28 days. Comparison of shrinkage results should always be made using the same specimen dimensions, curing regimen, and storage conditions.

4.1.2 ASTM C157/C157M as modified by ICRI 320.3R—ICRI 320.3R describes a modification of ASTM C157/C157M and makes recommendations for reporting properties appropriate for cement-based concrete repair materials. The standard test specimen is 3 in. (75 mm) square by 11-3/4 in. (300 mm), so the same surface area-to-volume ratio exists for mortar, extended mortar, and concrete. Non-polymer-cement materials are cured in a moist room for 24 hours, or for 2 hours after final setting time for rapid-hardening materials, and then demolded. Initial comparator readings are made based on final setting time as an indicator of development of sufficient strength to handle the bar. Polymer-cement materials are covered with polyethylene film immediately after casting, and demolded after 24 hours, or 2 hours after final setting time for rapid-hardening materials, in accordance with **ASTM C1439**. Initial comparator readings are made. The specimens are stored in a drying room or a water tank, and comparator readings are made at 3, 7, 14, 28, and 56 days. Measurements continue until 90% of the ultimate drying shrinkage or moisture expansion, as determined by **ASTM C596**, is attained.

4.1.3 ASTM C596—Length change during drying is determined for flowable mortar containing hydraulic cement and graded standard sand. Test specimens are 1 in. (25 mm) square by approximately 11-1/4 in. (285 mm). Specimens are moist-cured for 24 hours, demolded, and cured in lime-saturated water for 48 hours. Length comparator measurements follow. The specimens are then stored in air for 25 days, and length comparator measurements are made after 4, 11, 18, and 25 days of air storage. Typical shrinkage strains range from -0.05 to -0.15% . In general, shrinkage values more negative than -0.10% are considered too high for concrete repair (Vaysburd et al. 1999). Some concrete

repair materials have shrinkage values more negative than this criterion and may be inappropriate for use in applications where shrinkage may be an issue.

4.1.4 ASTM C806—This test method is typically used for comparative evaluation of expansive cements using a prescriptive mortar mixture. It is inappropriate for use with concrete repair mortars because the test specimens are cured under water continuously for 28 days while concrete repair mortars are usually exposed to air drying within 1 week after placement. Test specimens are 2 in. (50 mm) square by 10 in. (250 mm) long. A restraining cage, including a steel rod, is cast with the specimen. Immediately after casting, the specimens are covered with polyethylene sheets. After 6 hours, the specimens are demolded. The specimens are then cured in lime-saturated water for 28 days. Comparator measurements are made after 7 and 28 days, and the length change is calculated. A typical value for expansion is 0.06% under the conditions of this test.

4.1.5 ASTM C827/C827M—The early-age movements of cylindrical specimens of cementitious mixtures of paste, grout, mortar, and concrete are measured. Depending on the maximum-size aggregates, specimen size varies from 2 in. (50 mm) diameter by 4 in. (100 mm) high to 6 in. (150 mm) diameter by 12 in. (300 mm) high. Immediately after molding the specimens, an indicator ball is partially embedded in the top of each specimen. The test specimen is placed between a projected light source and a magnifying lens system, and movements of the ball are enlarged optically and measured on a wall chart. Measurements are made at 5-minute intervals for the first 90 minutes, at 10-minute intervals for the next hour, and at 20-minute intervals thereafter until the mixture has hardened. The change in height of the specimen is then calculated.

4.1.6 ASTM C1581/C1581M—This test measures the strains in a cylindrical specimen cast around a steel ring on a smooth, nonabsorbent, nonbonding surface, shown in Fig. 4.1.6. The specimens have an inside diameter of

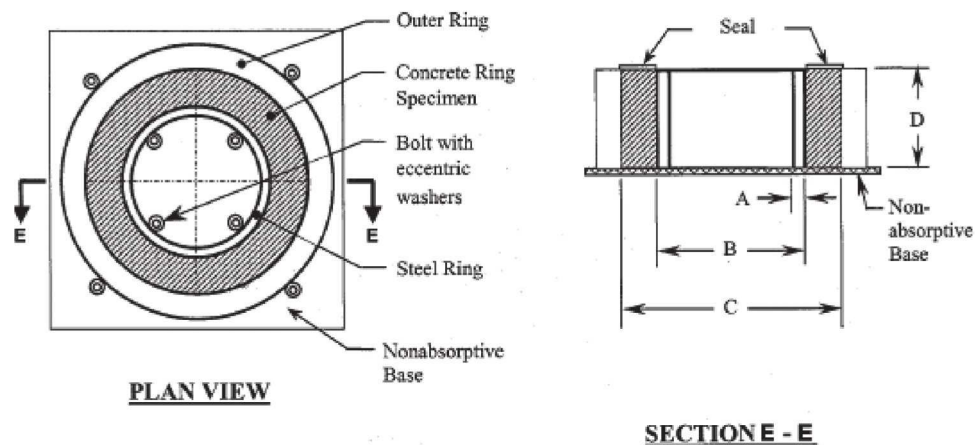


Fig. 4.1.6—Schematic of ASTM C1581/C1581M ring test specimen. (Reprinted with permission.)

13 in. (330 mm), an outside diameter of 16 in. (405 mm), and a height of 6 in. (150 mm). Unless otherwise specified, the specimens are wet-cured for 24 hours and then demolded, leaving the instrumented inner steel ring in place. The top surface is then sealed with paraffin wax or adhesive aluminum-foil tape. As the concrete repair material shrinks, strain is transferred to the steel ring, which is fitted with strain gauges. Strains are measured every 30 minutes maximum, and the specimens are visually inspected every 3 days maximum. The specimens are monitored for at least 28 days after initiation of drying unless cracking occurs prior to 28 days. The age at cracking is indicated when the strain suddenly decreases.

The test is intended to give a relative indication of when cracking due to restrained shrinkage may occur for different concrete repair materials. The results provide a comparative measure of a material's tendency to crack, which is affected by a combination of several material properties, including drying shrinkage, modulus of elasticity, tensile strength, strain capacity, and creep. Temperature changes and coarse aggregate effects are not considered.

4.2—Mechanical properties

Mechanical properties affect repair material interactions with the substrate concrete. It is essential that the repair material remain bonded to the concrete. It is also important that the repair material has mechanical properties compatible with those of the substrate concrete to ensure that the materials act as one and no material failure occurs. If some properties of the repair material are greatly different from those of the substrate concrete, such as the coefficient of thermal expansion, other properties should compensate for these differences for the repair to perform successfully. For example, a lower modulus of elasticity will reduce the horizontal shear stresses at the bond line due to differing thermal movements. Usually it is not necessary, or even desirable, for the repair material to have mechanical properties, such as compressive strength, tensile strength, or bond strength, substantially in excess of the substrate concrete, as any subsequent failures would simply occur in the weaker substrate concrete adjacent to the repair.

4.2.1 Elasticity—Elasticity is a material property that causes the material to recover its original size and shape after an applied deformation or force is removed. Elasticity is primarily important for materials intended to bridge active cracks, such as some crack sealants and surface coatings. Elasticity is typically quantified by measuring the elongation of a material in tension, as in [ASTM D638](#), discussed in [6.2.2](#).

4.2.2 Static modulus of elasticity—If the repair is not structural (not intended to share load with the substrate concrete), then it is typically desirable that the repair material have a modulus of elasticity lower than that of the substrate concrete, so it can more readily accommodate future movements within the repair material and at the interface between the repair material and substrate concrete. A lower modulus is particularly desirable if the repair material has volume stability or thermal compatibility properties that

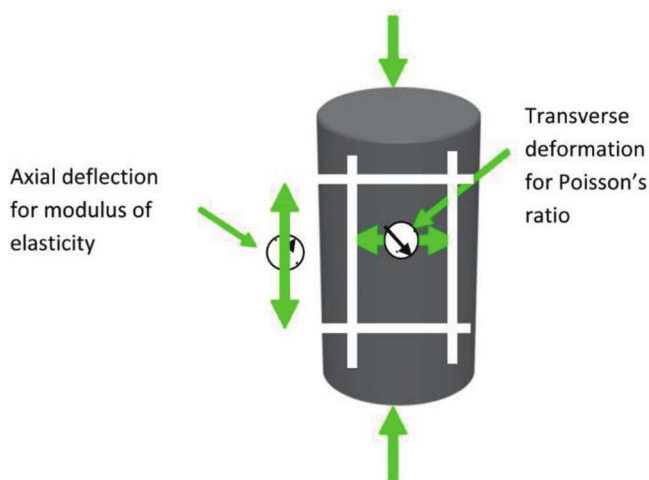


Fig. 4.2.2a—Schematic of ASTM C469/C469M test setup. (Courtesy of BASF Construction Chemicals, LLC.)

differ significantly from those of the substrate concrete. If a repair is intended to share load with the existing concrete substrate (structural repair), it is desirable for the moduli of elasticity of both materials to match as closely as possible. If the repair material has a higher modulus of elasticity, it will attract more of the applied load; if the repair material has a lower modulus of elasticity, it will deform under stress and transfer load into the substrate. Significant deviations can lead to uneven load distribution and system failure.

Two ASTM test methods typically used to measure the modulus of elasticity of repair materials are:

1. [ASTM C469/C469M](#)
2. [ASTM C580](#)

In ASTM C469/C469M, a molded cylindrical specimen or a drilled core specimen is loaded in compression and the axial deformation measured. Load-deformation data is plotted, and a chord modulus of elasticity is calculated for a stress corresponding to 40% of the ultimate load. The test setup is shown schematically in Fig. 4.2.2a. In ASTM C580, a square-bar beam specimen is loaded at midspan in flexure and the midspan deflection is measured. Load-deflection data are plotted, and a secant modulus of elasticity is calculated for a deflection that is 50% of the maximum deflection. The test setup is shown schematically in Fig. 4.2.2b. The results reported in stress units (psi or MPa).

4.2.3 Coefficient of thermal expansion—In situations where temperature is not controlled, such as in exterior and some interior applications, it is desirable for the repair material to have a coefficient of thermal expansion similar to that of the substrate concrete, so the two materials behave similarly under daily and seasonal temperature variations. If the coefficients vary significantly, the differential movements due to temperature fluctuations could affect the performance of the repair and should be accounted for in the repair design. The coefficient of thermal expansion for concrete typically ranges from 0.000002 to 0.000008/°F (0.000004 to 0.000014/°C), depending primarily on the aggregate type.

Four test methods are used to determine the coefficient of thermal expansion.

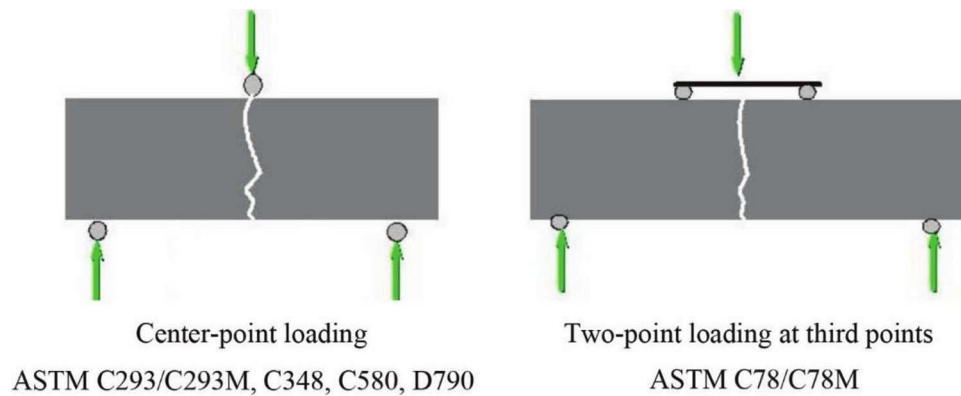


Fig. 4.2.2b—Schematics of flexural test setups. (Courtesy of BASF Construction Chemicals, LLC.)

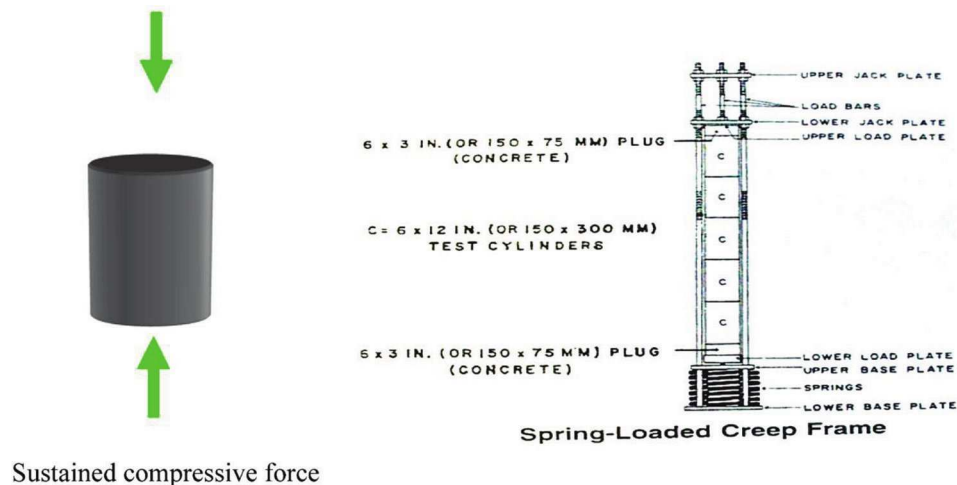


Fig. 4.2.4—Schematic of ASTM C512/C512M creep loading (reprinted with permission from ASTM C512/C512M) and spring-loaded creep frame. (Courtesy of BASF Construction Chemicals, LLC.)

1. **ASTM C531**
2. **ASTM D696**
3. **ASTM C884/C884M**
4. **USACE CRD-C39** modified

ASTM C531, ASTM D696, and United States Army Corps of Engineers (USACE) CRD-C39 are test methods in which the coefficient of thermal expansion is measured by determining the change in length of a material at constant humidity between two different temperatures: 73 and 210°F (23 and 100°C) in ASTM C531; and –22 and +86°F (–30 and +30°C) in ASTM D696. CRD-C 39 is modified in ICRI 320.3R to cycle from 140 to 40°F (60 to 4°C) at 50% relative humidity (RH) and greater than 95% RH. Results are reported as strain per unit temperature change. ASTM C884/C884M is a test method where thermal compatibility between concrete and an epoxy resin overlay is determined by a similar approach. In this case, a concrete substrate with an epoxy-resin overlay is cycled through a temperature range between 77 and –6°F (25 and –21°C) five times. If the epoxy resin overlay debonds from the concrete or there are horizontal cracks in the concrete near the interface, the epoxy resin system fails the test.

4.2.4 Creep—Because many repairs are not subjected to significant compressive forces, compressive creep may

not be a significant property of repair materials. Creep can be important in reducing stress induced in the repair material due to restraint of shrinkage strains or factors, such as thermal movement or the application of live loads.

Two ASTM test methods are used to evaluate compressive creep:

1. **ASTM C512/C512M**
2. **ASTM C1181/C1181M**

Both tests are suitable for testing repair materials.

In ASTM C512/C512M, creep is determined by placing a material under a sustained stress, usually not more than 40% of the compressive strength at the age of loading, measuring the resultant strain over time, and reducing the strain by measured strains from unloaded control specimens, which account for strains due to shrinkage. To determine the complete creep behavior of a repair concrete, test specimens are loaded at ages of 2, 7, 28, and 90 days, and 1 year. The creep strains are measured at specified intervals in the first year. Results are reported as percent strain at a given age for a given sustained stress. Creep may be determined for materials of different ages and under different curing regimens; however, variation from standard conditions should be explicitly reported. Figure 4.2.4 shows schematics of a typical creep test setup.

In **ASTM C1181/C1181M**, test specimens are conditioned for 7 days and then tested for 35 days. A test stress is selected and applied to the specimen, and the specimen deflection is measured. The specimen is then unloaded and placed in an oven at a selected temperature for 24 hours, after which the specimen is allowed to cool at 73°F (23°C) for 24 hours. The specimen is then reloaded to the selected stress and the deflection measured. This heating, cooling, loading, and deflection measurement cycle is repeated five times, with subsequent heating periods of 24, 72, and 48 hours, and 7 and 28 days. Creep is expressed as a graph of strain versus time in the oven.

Tensile creep is a significant property for repair materials. Tensile creep can reduce the cracking of repair materials by relaxing the tensile stress over time. No commonly accepted, standardized test method is available for measuring tensile creep, and there is no consensus regarding a correlation between tensile and compressive creep (Pigeon and Bissonnette 1999; Iriya et al. 2000; Beaudoin 1982).

4.2.5 Bond strength—Bond strength, or adhesion, relates to the ability of the two materials to act as one. This section addresses bond between the repair material and substrate concrete only.

A repair material should have sufficient bond strength to the substrate concrete so it does not separate from the substrate concrete once put into service. It is desirable for the bond strength to be higher than the minimum requirements so that any reductions due to field-application conditions are not as critical. Bond strengths that exceed the tensile strength of either the repair material or the substrate will induce failure in the weaker material if sufficient interface stresses result from shrinkage, thermal movement, or other factors.

Five test methods are used to measure bond strength:

1. **ASTM C882/C882M**
2. **ASTM C1042** (withdrawn 2008)
3. **ASTM C1404/C1404M** (withdrawn 2010)
4. **ASTM C1583/C1583M**
5. **ICRI 210.3R**

In these test methods, bond strength is usually inferred from the measured slant shear, direct tension, or direct shear test values, because failure rarely occurs at the bond line. Failures that occur away from the bond line imply that the bond strength is greater than the failure load in the test. When failure occurs at the bond line in direct tension tests, the measured tensile force is the actual bond strength. While ASTM C1042 and C1404/C1404M have been withdrawn, some material manufacturers still report bond strengths based on these procedures.

Slant shear bond tests (ASTM C882/C882M and C1042) measure the resistance to sliding between the repair material and concrete substrate along an inclined surface. The interface is subjected to combined shear and compressive stress. The measured bond strength may be influenced by the compressive strength of the substrate concrete and the surface roughness of the bonding surface.

Direct tension bond tests (ASTM C1404/C1404M, ASTM C1583/C1583M, and ICRI 210.3R) are more appropriate for repair applications because they apply a single

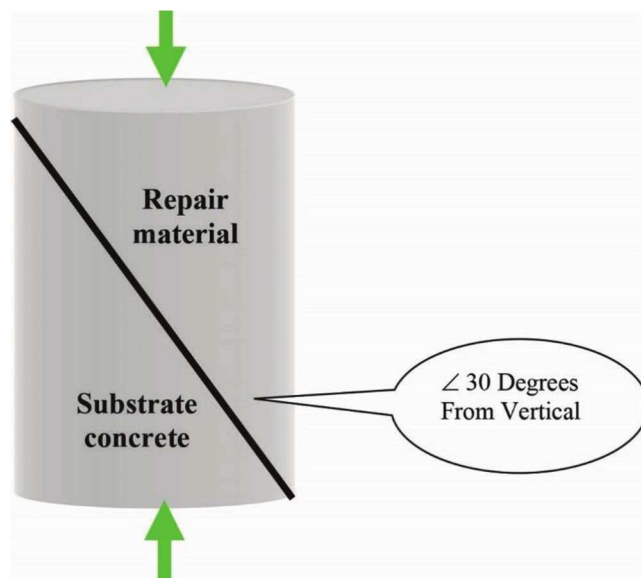


Fig. 4.2.5—Schematic of ASTM C882/C882M and C1042 slant shear tests. (Courtesy of BASF Construction Chemicals, LLC.)

mode of stress and direct tension at the bond interface. The ASTM C1404/C1404M test is a laboratory test for adhesive systems, while the ASTM C1583/C1583M and ICRI 210.3R tests use a cored specimen drilled through the repair material into the substrate. The latter three tests are suitable for field and laboratory evaluations.

ASTM C882/C882M and ASTM C1042 are slant shear bond tests specifically for epoxy-resin and latex bonding systems and are the most commonly reported test results. These tests involve casting a 3 x 6 in. (75 x 150 mm) right cylinder of substrate mortar or concrete using a dummy section to form a planar bonding surface that is 30 degrees off the longitudinal axis of the cylinder. The bonding surface is prepared by sandblasting or diamond sawcut (ASTM C1042 only), the bonding material is applied, and the test material is cast on top of the test specimen to complete the 3 x 6 in. (75 x 150 mm) right cylinder. At the appropriate age, the test specimen is loaded to failure in compression. The stress at fracture is determined by dividing the ultimate load by the elliptical area of the bonding surface to determine the bond strength. If the specimen does not fail at the bond line, the bond strength is considered, at least, the resulting failure stress. The substrate strength, porosity, surface roughness, moisture content, and other factors should be considered in evaluating values determined from these tests. Tests are shown schematically in Fig. 4.2.5.

ASTM C1404/C1404M is a direct tension test procedure that involves cutting a 3 x 6 in. (75 x 150 mm) concrete cylinder in half, creating a planar bonding surface perpendicular to the longitudinal axis of the cylinder. The cut surface is rubbed with abrasive paper, the adhesive being tested is applied to the cut surface, and a mortar overlay is applied, completing the 3 x 6 in. (75 x 150 mm) right cylinder. Steel pipe nipples are attached to the specimen, the nipples are screwed into pipe caps, the pipe caps are attached

to the test machine, and the specimen is loaded to failure in direct tension. Stress at fracture is determined by dividing the ultimate load by the cross-sectional area of the cylinder. If the specimen does not fail at the bond line, bond strength is at least the stress at fracture.

ASTM C1583/C1583M and **ICRI 210.3R** are test procedures that involve coring through a concrete repair or overlay material into the substrate concrete; adhering with epoxy a rigid plate or a machined, standard pipe cap with a minimum outside diameter of 2 in. (50 mm) to the core surface; and pulling along the core axis to failure at a rate of approximately 15 to 23 lb (70 to 100 N) per second. The failure type and load are recorded, and the failure load is reported in terms of psi (MPa).

Direct tension values below 100 psi (0.69 MPa) may indicate a serious problem with the repair material bond or substrate tensile strength. As the direct tension bond strength approaches 200 psi (1.4 MPa), the bond interface strength begins to approach the typical tensile strength of the concrete substrate, which is a limiting value of the overall repair (**Knab et al. 1989**).

4.2.6 Compressive strength—Three test methods are used to measure compressive strength:

1. **ASTM C39/C39M**
2. **ASTM C109/C109M**
3. **ASTM C579**

Compressive strength is determined by applying an increasing axial compression load until the specimen is unable to support additional load. The ultimate load is divided by the cross-sectional area to determine the ultimate failure stress (psi or MPa). ASTM C39/C39M tests cylindrical concrete specimens that are 4 x 8 in. (100 x 200 mm) or 6 x 12 in. (150 x 300 mm). ASTM C109/C109M tests 2 in. (50 mm) mortar cubes. ASTM C579 tests right cylinders 1 x 1 in. (25 x 25 mm) for materials with aggregates less than 1/16 in. (1.6 mm) in size; 2 in. (50 mm) cubes for materials with aggregates from 1/16 to 0.4 in. (1.6 to 10 mm) in size; and 2 in. (50 mm) minimum diameter right cylinders, with a height twice the diameter, for materials with aggregates larger than 0.4 in. (10 mm). A schematic of the test setup is shown in Fig. 4.2.6. Usually, it is desirable to have a compressive strength similar to that of the substrate concrete, but higher when necessary for strength or durability. The fracture pattern of the specimens should also be documented according to ASTM C39/C39M.

4.2.7 Tensile strength—Three test methods are used to measure tensile strength:

1. **ASTM C307**
2. **ASTM C496/C496M**
3. **USACE CRD-C164**

Tensile strength of cementitious materials is usually determined by a splitting tensile test (ASTM C307 and C496/C496M). The splitting tensile test applies a compressive force along the axis of an unconfined cylinder supported on its side, causing it to split along its axis, as shown schematically in Fig. 4.2.7a. Results are reported in stress (psi or MPa) and are normally of greater magnitude than direct tensile strength measurements (USACE CRD-C164). Direct

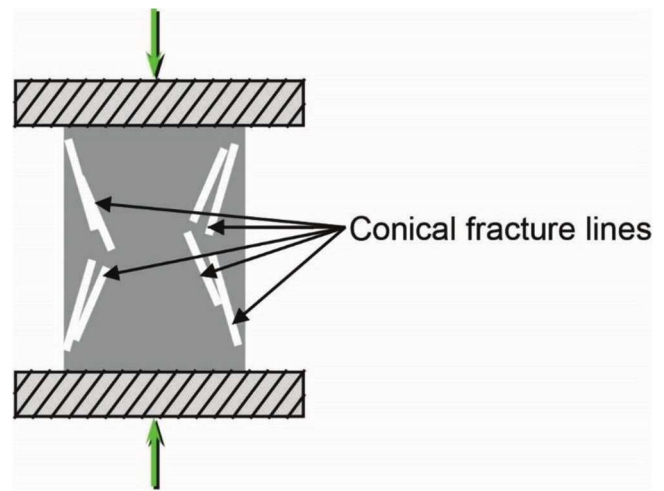


Fig. 4.2.6—Schematic of compression test setup (ASTM C39/C39M, C109/C109M, and C579). (Courtesy of BASF Construction Chemicals, LLC.)

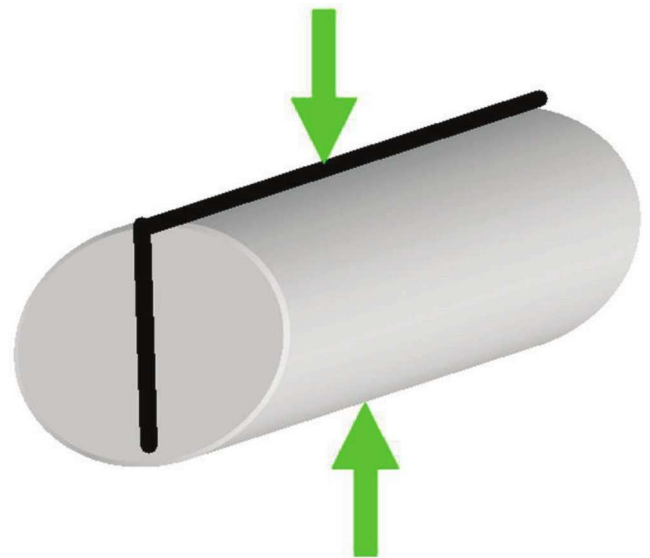


Fig. 4.2.7a—Schematic of splitting tension test setup (ASTM C307 and C496/C496M). (Courtesy of BASF Construction Chemicals, LLC.)

tensile strength measurements provide a true indication of the tensile strength of the material because the tensile stress is applied perpendicular to the failure plane. The direct tension test setup is shown schematically in Fig. 4.2.7b.

4.2.8 Flexural strength and modulus of rupture—Five test methods are used to measure the flexural strength of different repair materials:

1. **ASTM C78/C78M**
2. **ASTM C293/C293M**
3. **ASTM C348**
4. **ASTM C580**
5. **ASTM D790**

Flexural strength is determined by casting a beam specimen of a given material and testing it in bending. Tests use concrete beams supported at their ends with either one (ASTM C293/C293M, C348, C580, and D790) or two

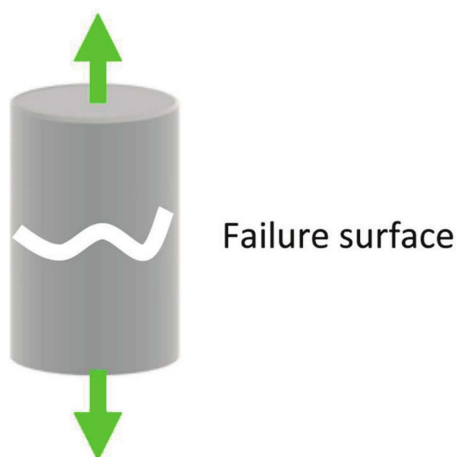


Fig. 4.2.7b—Schematic of direct tension test setup (USACE CRD-C164). (Courtesy of BASF Construction Chemicals, LLC.)

(ASTM C78/C78M) loading points, as shown schematically in Fig. 4.2.2b. The one-point loading at midspan creates the maximum tensile stress at a single cross section where the load is applied, whereas the two-point loading at the third points produces the maximum tensile stress over the middle third of the specimen, making the test less susceptible to scatter due to non-uniform material or the presence of large aggregate at the loading point. Tests have shown that the flexural strength from third-point loading could be approximately 75 psi (0.52 MPa) less than that obtained from center-point loading (PCA 1995). The resulting flexural strength is reported in stress units (psi [MPa]).

4.2.9 Significance of compressive, tensile, and flexural strengths—Compressive and flexural strengths are normally not the limiting properties in the performance of repair materials but may be used as general indicators of the material quality. Usually, it is desirable for these properties to meet or slightly exceed those of the substrate concrete (as measured at the time of the repair, not as originally specified). Higher tensile strength could be beneficial in reducing cracking due to restrained shrinkage and thermal contraction.

4.3—Constructability characteristics

Constructability characteristics are those material properties that affect or limit the installation or application of the repair material for varying field conditions, such as overhead or formed and poured repairs and hot or cold weather work.

4.3.1 Cohesiveness—The cohesiveness of a repair material is its ability to remain intact or not segregate during its application. Cohesiveness of repair material is important for the ease of construction and uniformity of repair. For example, in concrete repairs on vertical and overhead surfaces, a more cohesive material can be applied in thicker lifts with less chance of internal separations or debonding before setting.

4.3.2 Viscosity—The measured value of viscosity is affected by factors such as the method of measurement (viscometer or rheometer geometry), temperature, and the rate of applied shear strain. Materials with low viscosity flow more freely than those with higher viscosity. In general,

low-viscosity materials are used to repair cracks and penetrate concrete pores. Flowable, self-consolidating materials are also available for concrete repairs. Flowable is generally considered a concrete material with a slump greater than 7.5 in. (190 mm) while maintaining cohesive nature (ASTM C1017/C1017M).

4.3.3 Working time—Factors such as ambient and material temperature, mixing ratio, and mass of material can significantly affect the amount of time available for the applicator to spread the material. Consequently, it is difficult to test for and report working time in a meaningful manner. A material may be unworkable before initial set occurs, so that working time is less than or equal to initial set time. Working times are often reduced for high-early-strength and very high-early-strength materials. These materials are defined by Strategic Highway Research Program (SHRP) SHRP-C-363 defines very high-early-strength material as 2000 psi (13.8 MPa) minimum compressive strength 6 hours after mixing.

4.3.4 Environmental considerations—Repair material should be suitable for the specific repair application environment. For example, some environmental limitations at the time of construction include the air and concrete temperatures, amount of moisture on the substrate concrete surface, relative humidity, wind speed (if the repair area is in direct sunlight or shade), and anticipated climatic conditions that occur before the repair material reaches its final set. The choice of specific repair materials and their corresponding properties depends on actual construction conditions. In some cases, the construction conditions are modified to fit the properties of the repair materials chosen.

4.4—Aesthetic properties

The appearance of repair materials is important in some circumstances, including the following properties.

4.4.1 Surface texture—Unless a change in aesthetics is explicitly desired, the surface texture of the repair material generally should match that of the adjacent material.

4.4.2 Color—Unless a change in aesthetics is explicitly desired, the color of the repair material generally should match that of the adjacent material, unless the repair is not visible, such as after the application of a coating.

4.4.3 Aging—Some repair materials will change appearance as they age due to weathering, exposure to ultraviolet (UV) light, drying, or curing.

4.4.4 Moisture absorption—The appearance of repair material may change when it gets wet, and it may return to its original appearance as it dries. Changes in appearance may be different from the adjacent concrete.

4.5—Factors affecting durability

Service conditions can place various demands on the repair material, possibly requiring the repair material to have enhanced properties for long-term durability. Conditions can include exposure to moisture, temperature variations, chemicals, and mechanical wear.

4.5.1 Resistance to freezing and thawing—Some repair materials, including concrete, are susceptible to deterioration when exposed to cycles of freezing and thawing in a satu-

rated condition. The expansion and migration of water can generate destructive internal pressures unless measures such as air entrainment are taken to provide the needed durability.

Three test methods are used to evaluate resistance to cyclic freezing and thawing:

1. **ASTM C666/C666M**
2. **ASTM C672/C672M**
3. ASTM C672/C672M as modified by **ICRI 320.2R**

Durability of material in freezing environments is evaluated in bulk by ASTM C666/C666M, or as a surface scaling effect by ASTM C672/C672M and modified by ICRI 320.2R. The approach in ASTM C666/C666M is to expose concrete or a cementitious material to freezing-and-thawing cycles and record the change in dynamic modulus of elasticity and mass loss of the specimens. ASTM C672/C672M relies on a visual inspection of surface damage caused by freezing-and-thawing cycles of a ponded salt solution, while the ICRI 320.2R modification includes measuring the mass loss of the scaled material to quantify the amount of scaling. While ASTM C672/C672M has been withdrawn, some manufacturers still report results of this test.

ASTM C666/C666M—This test method includes two procedures. Procedure A is with both freezing and thawing in water, and Procedure B is with freezing in air and thawing in water. Procedure A is the most commonly used because it is more easily automated. A complete test consists of 300 freezing-and-thawing cycles, unless the relative dynamic modulus of elasticity of the specimen first reaches 60% of the initial value. A durability factor, as calculated in the test procedure, which is greater than 80, is generally considered to represent a material that will be durable under freezing-and-thawing conditions. If this test is not carried out to 300 cycles, the total number of cycles should be reported. ASTM C666/C666 is considered a severe test method; some materials that fail the test may not fail under harsh service conditions.

ASTM C672/C672M—This test method, commonly called the salt scaling test, is appropriate for materials exposed to freezing-and-thawing cycles in conjunction with deicing salt exposure. A 4% solution of calcium chloride is ponded on the specimen surface and subjected to cyclic freezing and

thawing. Each cycle lasts 24 hours and, generally, 50 cycles are sufficient to evaluate a surface. Test results use a subjective visual scale of 0 to 5, with 0 indicating no scaling and 5 indicating severe scaling. Refer to Fig. 4.5.1 for a schematic of the test setup.

ICRI 320.2R provides a modification of ASTM C672/C672M that is often used to eliminate subjectivity of the standard test. The modification involves collecting, drying, and weighing the scaled material to quantify the mass loss from surface deterioration after every 10 cycles. A value less than 0.10 lb/ft² (0.5 kg/m²), after 50 cycles, usually denotes acceptable performance.

As durability of the concrete surface improves with age, the age of test specimens when initially exposed to the freezing-and-thawing cycling is critical to interpreting the results. ASTM C672/C672M, with or without the ICRI 320.2R modification, has been found to be a severe test method; some materials that fail the test may not fail under harsh service conditions. ASTM C672/C672M, with or without the ICRI 320.2R modification, has also been found to be sensitive to surface finishing techniques (Johnston 1993). Conducting the test on a formed versus finished face of a specimen can significantly affect the results.

4.5.2 Permeability—The permeability of a repair material is important in environments where the repair material or substrate concrete is vulnerable to moisture-related deterioration such as freezing-and-thawing damage of saturated concrete, corrosion of embedded reinforcing steel, alkali-aggregate reactions, or sulfate attack. Permeability is particularly sensitive to the age of the material being tested. Generally, permeability decreases as the cementitious material hydrates or as the level of carbonation increases. Tests should always indicate the specimen age at the time of the test.

Five test methods are used to measure permeability:

1. **AASHTO T 259**
2. **ASTM C1543**
3. **AASHTO T 277**
4. **ASTM C1202**
5. **ASTM C642**

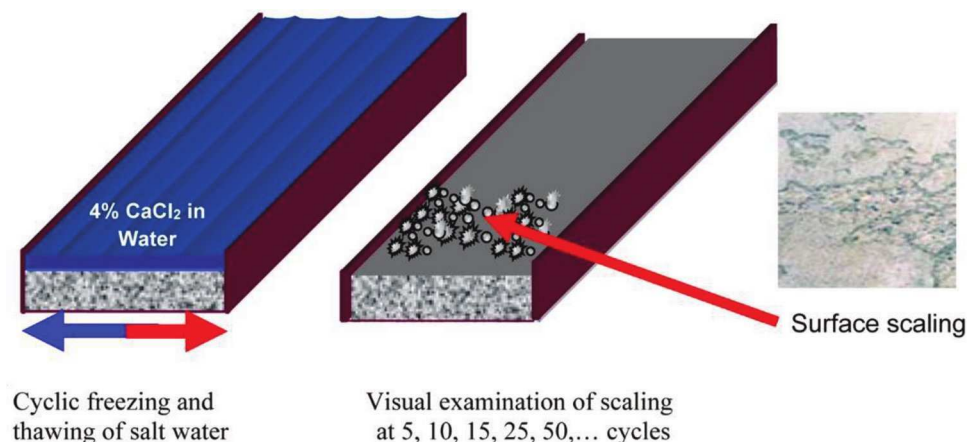


Fig. 4.5.1—Schematic of ASTM C672/C672M freezing-and-thawing test setup. (Courtesy of BASF Construction Chemicals, LLC.)