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Guide for the Selection of Materials for the Repair of Concrete

Reported by ACI Committee 546

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Guide for the Selection of Materials for the Repair of Concrete

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

Keywords: cementitious; concrete; epoxy; polymer; polyurethane; repair; silica fume; test methods.

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CHAPTER 1—INTRODUCTION

1.1—Background

Concrete is inherently a durable material, but its durability under any given set of exposure conditions varies with the concrete mixture proportions; the presence and positioning of reinforcement; and the detailing, placing, finishing, curing, and protection it received. In service, it may be exposed to conditions of abrasion, moisture cycles, cycles of freezing and thawing, temperature cycles, corrosion of reinforcement, and chemical attack. Deterioration of the concrete and the potential reduction of its service life can result.

Thus, as the concrete industry has developed and grown from its beginnings, repair of concrete has always been needed; however, with the ever increasing size of the infrastructure in all parts of the world, its age, the frequent deferral of maintenance, and the increased public awareness of deterioration and maintenance needs, repair has become a major focus of design and construction activities. The repair of concrete, however, has traditionally been as much an art as a science. Engineers and contractors typically have not received much formal training in techniques for repair and performance of repair materials applied to concrete. Personal experience may be a good teacher, but it can take a long time and be costly in terms of failed repairs. Although the situation is changing, there is still much too little information available to reliably predict the performance or service life of repairs. Too many concrete repairs fail prematurely, with the result being economic loss and the need to do the repair again.

Due to the greatly expanded repair market, new materials and repair methods are being introduced at an increasing rate to the construction market. At the same time, due to changing environmental, building code, and other regulations, many existing, well-proven products are being reformulated into essentially new products that have little track record, if any. The user may or may not be informed of these changes. Many new or reformulated products enter the market each year.

It is often difficult for a specifier to find the appropriate data needed to systematically evaluate a product in a logical fashion for a given repair situation. Often, test data are not available or, if they are, either they are not presented in useful or appropriate terms or the data are presented in a manner that precludes comparison with other competing materials (that is, through the use of nonstandard or modified test methods).

There are many competent repair materials available commercially. There are also, however, many unsubstantiated claims for suitability and success. Even the highest-quality materials do not perform as expected if they are used inappropriately.

In 1996, ACI published the "Concrete Repair Guide (ACI 546R)." This was the first ACI publication devoted entirely to the subject of general concrete repair. As the first publication of its kind, its principle emphasis was on techniques for concrete repair. It contained only limited information on the appropriate selection of the repair material. The physical properties of repair materials govern their performance in service and, as a result, the appropriate selection of these materials for a given repair is at least as important to a successful, long-lasting repair as is using the proper procedures and workmanship. This guide is the second in a series of documents prepared by ACI Committee 546 to aid the user in specifying and executing typical concrete repairs.

1.2—Essential steps of concrete repair

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

1. A condition survey with a scope consistent with the perceived condition of the structure and the owner's repair objectives, performed by qualified individuals, to document and evaluate visible and nonvisible defects and damage, as well as potential damage;

2. An assessment of the application and service conditions to which the concrete repair material is, or will be, exposed;

3. Determination of the cause of the damage or deterioration necessitating the repair; for example, mechanical damage such as impact or abrasion; design, detailing or construction deficiencies; chemical damage, such as alkali-aggregate reaction; physical damage related to cycles of freezing-and-thawing or thermal movements; and corrosion of the steel reinforcement caused by improper placement, carbonation of the concrete, or chloride ingress into the concrete;

4. Determination of the repair objectives, including desired service life; and

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

Once the concrete to be repaired has been evaluated and the cause of the distress established, the details of the proposed repair can be developed. This includes the evaluation and determination of the needed physical properties of the repair materials. The appropriate repair material can then be selected from those available. This selection is usually based on the ability of the material to satisfy the repair constraints and objectives as defined herein, plus considerations of cost and availability.

Finally, the repair can be implemented, including protective systems if designed as part of the repair. The reader is directed to ACI 546R, where these steps are discussed in further detail.

1.3—Objective

The objective of this guide is to provide guidance for the selection of materials for the repair of concrete. To provide guidance the following information is provided:

- Common repair materials are identified;
- Relevant material properties are discussed;

- Test procedures for measuring these properties are listed and discussed;
- Minimum test values or performance levels are recommended; and
- The importance of various material properties are discussed for various repair material application and service environments.

1.4—Scope

This guide covers material selection for the following types of repair:

1. Concrete replacements, categorized on the basis of the depth and orientation of the repair;
2. Overlays categorized on the basis of their thickness; and
3. Crack repairs, which are categorized on the basis of their stability, width, and other service conditions.

Materials covered by this guide for concrete replacements and overlays include:

- Portland or blended cement-based mortar and concrete;
- Portland or blended cement-based silica-fume mortar and concrete;
- Portland or blended cement-based polymer-cement mortar and concrete;
- Magnesium-ammonium-phosphate-cement mortar and concrete; and
- Polymer-based mortar and concrete.

Materials covered by this guide used for crack treatment include:

- Epoxy resin;
- High-molecular-weight methacrylate;
- Polyurethane chemical grout;
- Polyurethane sealant;
- Silicone sealant;
- Polymer grout;
- Polymer-cement grout;
- Cementitious grout; and
- Strip and seal systems, including preformed flexible sheets.

Tables 2.1 and 2.2 present a summary of available test methods and typical test values for concrete replacement materials and crack repair materials, respectively. The test values in Table 2.1 are for portland-cement concrete; values for other concrete replacement materials will be added in the next edition of the guide. ACI 503R, 548.1R, and 548.3R can be referred to for information on polymer-cement and polymer concrete replacement materials. The test methods included in Table 2.2 are, in general, not discussed in the text of Chapter 2; again, this discussion will be added in the next edition of the guide. ACI 224.1R, 504R, and 503.5R can be referred to for information on crack repair materials. Finally, surface treatments such as coatings and penetrating sealers are beyond the scope of this document.

Repair material specifiers and users should be aware that many repair materials have to be handled with care to avoid potential harm to workers and the environment.

1.5—Definitions

In this guide, the term "concrete replacement" is used to refer to the removal and replacement of damaged or deteriorated concrete. Concrete replacement includes partial-depth and full-depth repairs. Such repairs are sometimes informally called patches.

The term "alkali-aggregate reaction" is used herein to refer to all cases of reactive aggregate, such as alkali-silica or alkali-carbonate reactions.

The reader is directed to ACI 116R and ICRI "Concrete Repair Terminology" (ICRI 2002) for a comprehensive list of terminology and definitions used in this document.

1.6—Special repair and service environments

This guide covers concrete repair materials for common types of concrete construction. Special repair and service environments may require repair materials with enhancement of particular properties. For the repair of environmental structures or mass-concrete structures, underwater repairs, and other special repair and service environments, refer to the recommendations of industry groups, such as ACI Committee 350, for specific guidance in repair material selection.

1.7—Current industry issues and concerns

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

- Material test methods and reporting of test data;
- Curing of repair materials and manufacturers' reported test results;
- Product limitations and warnings;
- Standardized industry acceptance;
- Repair material bond;
- Corrosion reduction;
- Structural repairs; and
- Ongoing developments.

CHAPTER 2—PROPERTIES OF REPAIR MATERIALS AND THEIR IMPORTANCE

2.1—General

Compatibility between the properties of repair materials and the intended substrate is an important consideration. For example, in many concrete replacement applications, the properties of the repair materials, such as the coefficient of thermal expansion and creep, should be as similar as possible 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 that will perform better than the base concrete in the service environment. In any case, it is necessary to know the properties of the repair materials and the substrate before a decision is made on the approach to be taken for a particular repair (McDonald et al. 2002).

Many properties of repair materials and of existing concrete are time dependent. In all cases where material properties are specified, the corresponding age of the materials should be noted. A conclusion derived from Alberta Transportation's 1987 concrete replacement testing program was that the durability of concrete replacement materials correlated better with long-term physical properties (that is, 1 year or more after placement) rather than shorter-term physical properties (24-hour and 28-day properties) (Gurjar 1987).

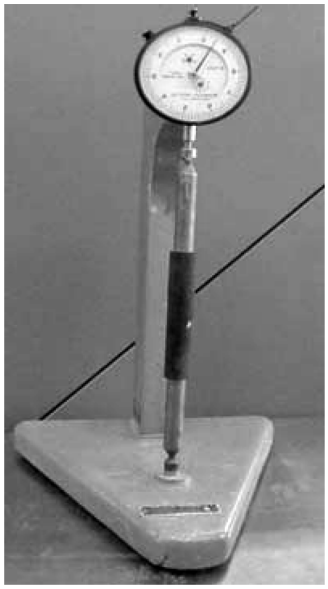


Fig. 2.1—Length comparator with standard calibrating rod, used for ASTM C 157/C 157M.

The user should note that most test methods cited in this guide are performed at standard conditions, essentially at room temperature in many cases, with standard-sized specimens, and that the reported properties may not reflect the actual properties of the repair material in various-sized repairs in service conditions.

This chapter discusses properties of repair materials and test methods used to evaluate them. Some of the test methods are not specifically applicable for certain repair materials or repair applications, but may be useful for comparing repair materials. The descriptions of the various test methods are brief. The reader should consult the referenced standards themselves for details. Material manufacturers should provide test data based on ASTM standards and other standardized test methods. The ICRI "Guideline for Repair Material Data Sheet Protocol" (ICRI 2003) describes 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.

2.2—Volume stability

Volume stability refers to initial and long-term changes in the linear dimensions or volume of the repair material after placement. Volume stability properties affect the compatibility of the repair material with the substrate concrete. The substrate concrete is usually relatively stable, with minimal residual creep and shrinkage deformations; however, the substrate concrete may experience some volume instability for various reasons, including seasonal environmental changes such as thermal expansion and contraction. Any shrinkage or expansion of the repair material should occur before the repair material has reached its final set (when creep is high), or it should be accommodated in some manner in the repair design, such as the use of control joints, curing, avoidance of reentrant corners, and avoidance of high length-width ratio configurations.

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; however, these materials are subject to greater volume changes due to temperature variations. Significant changes in the repair material volume can cause high shear stresses at the interface, debonding from the substrate concrete, and cracking of the repair material. Stresses created in the 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 repair material may be resisted by keying it into the substrate concrete or by otherwise providing restraint or confinement. Cracking of the repair material to relieve restrained shrinkage should be anticipated, and further repairs may be needed.

Six test methods are used to evaluate volume stability:

- ASTM C 157/C 157M;
- ASTM C 157/C 157M, as modified by ICRI "Guideline for Repair Material Data Sheet Protocol" (2003);
- ASTM C 596;
- ASTM C 806;
- ASTM C 827; and
- ASTM C 1581.

ASTM C 157/C 157M, C 596, and C 806 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 C 806 to restrain the specimen expansion. ASTM C 827 is a test method that involves monitoring the height of cylindrical test specimens until the specimens harden. ASTM C 1581 is a test procedure that involves measuring the strains and observing cracking in donut-shaped specimens with inner steel rings. The primary use of all of these test methods is to provide a relative comparison of various materials when tested in the same fashion. The actual shrinkage experienced in the field will likely be greater than the shrinkage reported from the tests.

ASTM C 157—The curing and comparator reading regimen in this test method is not applicable for repair mortars and concretes. The test specimens are 285 mm (11-1/4 in.) long and vary in cross section from 25 mm (1 in.) square for mortar specimens to 75 or 100 mm (3 or 4 in.) 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 15 to 30 minutes. Initial length comparator measurements are then made. The specimens are then stored in lime-saturated water for another 27 days, and another set of length comparator measurements are made. Following 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. The length change, in percent, at any age is then calculated. Typical shrinkage strains range from 0.02% expansion to 0.12% shrinkage. The length comparator setup is shown in Fig. 2.1.

Neither of the curing regimens is representative of field conditions for most repair mortars because the initial length

comparator measurement is made at 24 hours, ignoring volume changes within the first 24 hours, extensive wet curing is used, and the specimens are not restrained. In field conditions, the bonding of the repair material to the substrate concrete provides restraint to shrinkage.

When testing shrinkage-compensating mortars, unrealistic curing conditions and inappropriate comparator reading schedules can 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 the 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 the shrinkage results. A 25 mm (1 in.) square specimen shrinks more quickly than 75 or 100 mm (3 or 4 in.) square specimens. If larger specimens are used, it may be appropriate to consider shrinkage at 16 weeks instead of 28 days.

ASTM C 157/C 157M, as modified by ICRI (2003)—ICRI (2003) describes a modification of ASTM C 157/C 157M and makes recommendations for reporting properties appropriate for cement-based repair materials. The standard test specimen is 75 mm (3 in.) square by 300 mm (11-3/4 in.), so the same surface area-volume ratio exists for mortar, extended mortar, and concrete. Non-polymer-cement materials are cured in a moist room for 24 hours, or 2 hours after final setting time for rapid hardening materials, and demolded. Initial comparator readings are then made based on 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 C 1439. Initial comparator readings are then made. The specimens are then stored in a drying room or a water tank, and comparator readings are made at ages of 3, 7, 14, 28, and 56 days. Measurements continue until 90% of the ultimate drying shrinkage, as determined by ASTM C 596, is attained.

ASTM C 596—The length change on drying is determined for flowable mortar containing hydraulic cement and graded standard sand. The test specimens are 25 mm (1 in.) square by 285 mm (11-1/4 in.). Specimens are moist cured for 24 hours, demolded, and then cured in lime-saturated water for 48 hours. Length comparator measurements are then made. The specimens are then stored in air for 25 days, and length comparator measurements are made after 4, 11, 18, and 25 days. Typical shrinkage strains range from –0.05 to –0.15%. In general, shrinkage values greater than –0.10% are considered too high for concrete repair (Vaysburd et al. 1999). By this criterion, many repair materials are inappropriate in applications where shrinkage may be an issue.

ASTM C 806—This test method is typically used for comparative evaluation of expansive cements using a prescriptive mortar mixture. It is inappropriate for use with repair mortars because the test specimens are cured under water continuously for 28 days while repair mortars are usually exposed to air drying within 1 week after placement. The test specimens are 50 mm (2 in.) square by 250 mm (10 in.) long. A restraining cage, including a steel rod, is cast with the specimen. Immediately after casting, the specimens are covered with polyethylene sheets for 6 hours, when 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 expansion or shrinkage is calculated. A typical value for expansion is 0.06% under the conditions of this test.

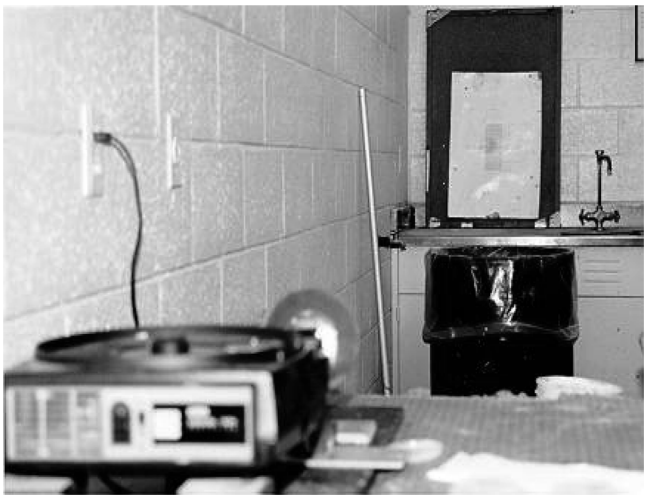


Fig. 2.2—Test setup for ASTM C 827 with slide projector and lens (disk in front of projector) in foreground and calibrated chart on wall background.

ASTM C 827—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 sizes vary from 50 mm (2 in.) diameter by 100 mm (4 in.) high to 150 mm (6 in.) diameter by 300 mm (12 in.) high. Immediately after molding the specimens, a metal indicator ball is partially embedded in the top of the specimen. The test specimen is placed between a projector and a lens, as shown in Fig. 2.2, and movements of the ball are enlarged optically and measured on the 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 until the mixture has hardened. The change in height of the specimen is then calculated.

ASTM C 1581—This test measures the strains in a cylindrical specimen cast around a steel ring, shown in Fig. 2.3. The specimens have an inside diameter of 330 mm (13 in.), an outside diameter of 406 mm (16 in.), and a height of 152 mm (6 in.). Unless otherwise reported, the specimens are wet-cured for 24 hours, and then demolded. The top surface is then sealed. As the repair material shrinks, strain is applied to the steel ring, which is fitted with strain gauges. Strains are measured every 30 minutes, and the specimens are visually inspected every 2 to 3 days. The specimens are monitored for 2 weeks after cracking. The appearance of the first crack is indicated when the strains measured at one or more strain gauges suddenly decreases. The test is intended to give a rela-

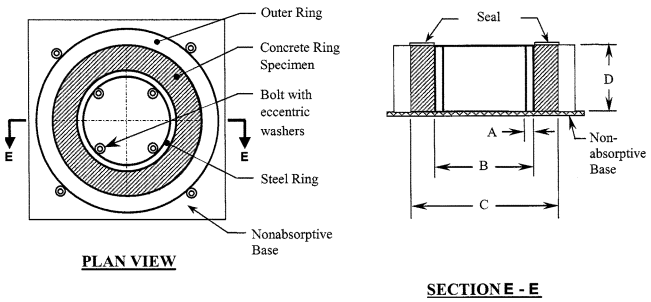


Figure Dimensions	Inch-Pound Units	SI Units
A	0.50 ± 0.12 in.	12.5 ± 0.13 mm
B	13.0 ± 0.12 in.	330 ± 3 mm
C	16.0 ± 0.12 in.	406 ± 3 mm
D	6.0 ± 0.25 in.	150 ± 6 mm

Fig. 2.3—Schematic of ASTM C 1581 ring test specimen (from ASTM C 1581).

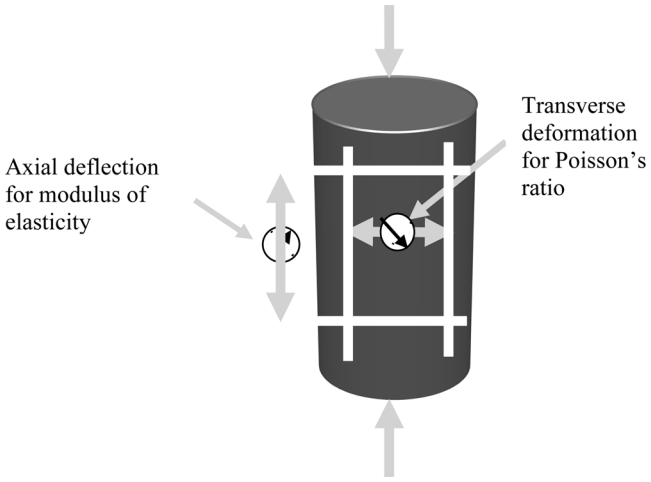


Fig. 2.4—Schematic of ASTM C 469 test setup.

tive indication of when cracking due to restrained shrinkage may occur for different 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.

2.3—Mechanical properties

Mechanical properties affect repair material interactions with the substrate concrete. In most cases, it is essential that the repair material remains 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 will act as one and no material failure will occur. 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 to reduce thermal stresses. It is usually not necessary, or even desirable, for the repair material to have some 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.

2.3.1 *Elasticity*—Elasticity is the property of a material that causes it 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 D 638.

2.3.2 *Modulus of elasticity*—The modulus of elasticity is the ratio of normal stress to corresponding strain for tensile or compressive stress below the proportional limit of the material. If the repair is not structural (that is, 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 the substrate concrete so it can more readily accommodate future movements both within the repair material and at the interface between the repair material and the substrate concrete. A lower modulus is particularly desirable if the repair material has volume stability or thermal compatibility properties that differ significantly from those of the substrate concrete. If a repair is intended to share load with the existing structure (a 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.

The following two ASTM test methods are typically used to measure the modulus of elasticity of repair materials:

- ASTM C 469; and
- ASTM C 580.

In ASTM C 469, a molded cylindrical specimen or a drilled core specimen is loaded in compression, and the axial deformation is measured. The load-deformation data are 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. 2.4. In ASTM C 580, a square-bar beam specimen is loaded at midspan in flexure, and the midspan deflection is measured. The 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 described and shown schematically in Section 2.3.8. The results are reported in stress units (MPa or psi).

2.3.3 *Coefficient of thermal expansion*—The coefficient of thermal expansion is the change in linear dimension per unit length of a material per degree of temperature change. 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 that 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

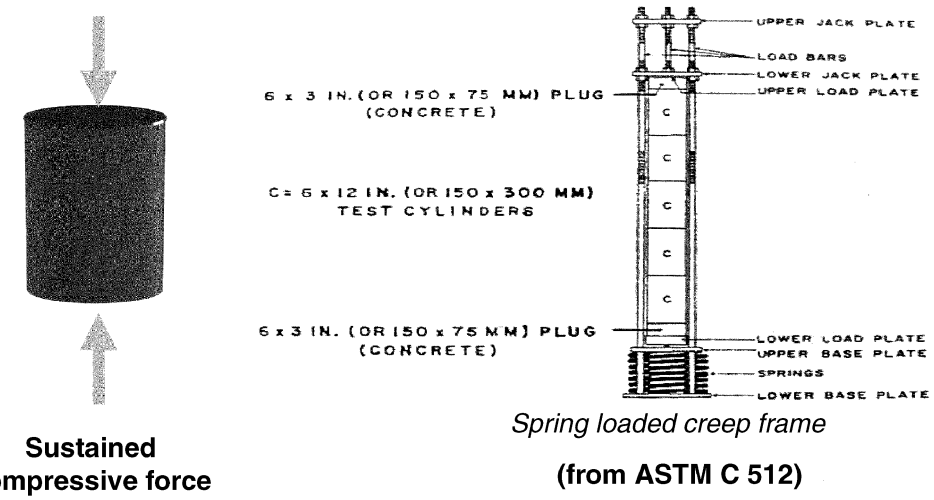


Fig. 2.5—Schematic of ASTM C 512 creep loading and spring-loaded creep frame.

typically ranges from 4×10^{-6} to 14×10^{-6}/°C (2×10^{-6} to 8×10^{-6} /°F), depending primarily on the aggregate type.

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

- ASTM C 531;
- ASTM D 696;
- CRD-C 39; and
- ASTM C 884/C 884M.

ASTM C 531 and D 696 and CRD-C 39 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, typically 4 and 60 °C (40 and 140 °F). Results are reported as strain per unit temperature change. ASTM C 884/C 884M is a test method in which 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 25 and –21 °C (77 and –6 °F) five times. If the epoxy resin debonds or if either material shows cracking, the epoxy resin fails the test.

2.3.4 *Creep*—Creep is time-dependent deformation due to sustained load. 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 if stress is induced in the repair material due to restraint of shrinkage strains or due to factors such as thermal movement or the application of live loads.

Two ASTM test methods are used to evaluate compressive creep:

- ASTM C 512; and
- ASTM C 1181.

In ASTM C 512, creep is determined by placing a material under a sustained stress, usually 40% of compressive strength, measuring the resultant strain over time, and comparing measured strains with unloaded control specimens. The test specimens may be 2, 7, 28, or 90 days old at the start of the testing, and the creep strains are measured at specified intervals for 1 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, variations from standard conditions should be explicitly reported. Figure 2.5 shows schematics of a typical creep test setup.

In ASTM C 1181, test specimens are conditioned for 7 days and are then tested for 35 days. A test stress is selected, applied to the specimen, and the specimen deflection is measured. The specimen is then placed in an oven at a selected temperature for 24 hours, after which the specimen is allowed to cool at 23 °C (73 °F) for 24 hours. The specimen is then reloaded to the selected stress, and the deflection is measured. This heating, cooling, loading, and deflection measurement cycle is repeated five times, with subsequent heating periods of 24, 48, and 72 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. 1999, 2000; Beaudoin 1982).

2.3.5 *Bond strength*—Bond strength (adhesion) is the resistance of the repair material to separation from the substrate concrete, from reinforcing steel or from other materials with which it is in contact. It relates to the ability of the two materials to act as one. This section addresses bond between the repair material and the substrate concrete only.

It is essential that a repair material has sufficient bond strength to the substrate concrete such that the repair does not separate from the substrate concrete. It may be desirable for the bond strength to be larger 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 the substrate will induce failure in the substrate if sufficient interface stresses result from shrinkage, thermal movement, or other factors.

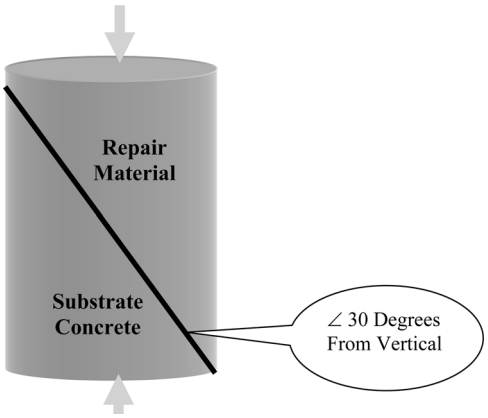


Fig. 2.6—Schematic of ASTM C 882 and C 1042 slant shear tests.

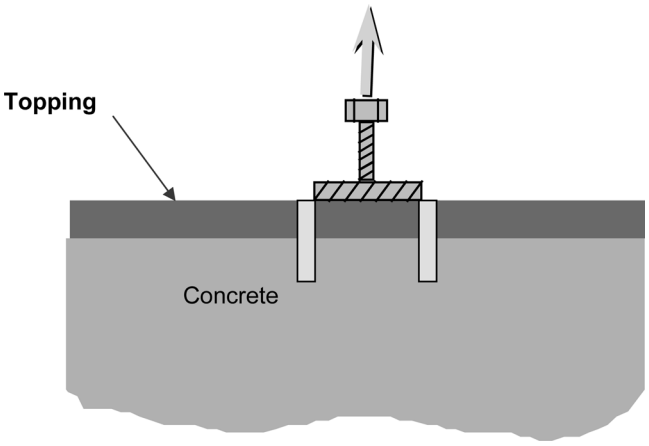


Fig. 2.7—Schematic of direct tension bond test setup (ACI 503R and CSA A23.2-6B).

Six test methods are used to measure bond strength:

- ASTM C 882;
- ASTM C 1042;
- ASTM C 1404/C 1404M;
- ACI 503R;
- CSA A23.2-6B;
- ASTM C 1583;
- ICRI Guideline No. 03739 (ICRI 2004); and
- Michigan Department of Transportation (MDOT) direct shear bonding test.

In these test methods, bond strength is usually inferred from the measured slant shear, direct tension, or direct shear test values, because the 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.

Slant shear bond tests (ASTM C 882 and C 1042) measure the resistance to sliding between the repair material and the concrete substrate along an inclined surface. The interface is subjected to combined shear and compressive stress. The measured bond strength is somewhat suspect in that the results have been found to be highly dependent on the compressive strength of the substrate concrete and the surface roughness of the bonding surface. Direct tension bond tests (ASTM C 1404/C 1404M, ACI 503R, CSA A23.2-6B, ASTM C 1583, and ICRI Guideline 03739) are more appropriate for repair applications because they apply a single mode of stress, direct tension, at the bond interface. The ASTM C 1404/C 1404M test is a laboratory test for adhesive systems, while the ACI 503R, CSA A23.2-6B, ASTM C 1583, and ICRI Guideline 03739 tests use a cored specimen drilled through the repair material into the substrate. The latter four tests are suitable for both field and laboratory evaluations. ASTM C 1583 and ICRI Guideline No. 03739 test procedures were introduced in 2004, so have had only limited time for industry use. The MDOT direct shear bonding test measures the shear applied along the interface between the repair material and the substrate concrete.

ASTM C 882 and C 1042—These slant shear bond tests are used for the most commonly reported test results. These tests involve casting a 75 x 150 mm (3 x 6 in.) 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, and the test material is cast on top of the substrate to complete the 75 x 150 mm (3 x 6 in.) 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 to be at least the resulting failure stress. The substrate strength, porosity, surface roughness, moisture content, and other factors need to be considered in evaluating values determined from these tests. The minimum acceptable bond strength value of 10.0 MPa (1500 psi) required by ASTM C 882 is generally accepted as adequate; however, it was originally developed as a criterion for epoxy bonding to hardened concrete, and correlation with the field performance of cementitious materials is not known. The tests are shown schematically in Fig. 2.6.

ASTM C 1404/C 1404M—This direct tension test procedure involves cutting a 75 x 150 mm (3 x 6 in.) substrate cylinder in half, creating a planar bonding surface perpendicular to the longitudinal axis of the cylinder. The bonding surface is prepared and the test material is applied, completing the 75 x 150 mm (3 x 6 in.) right cylinder. Typically, steel plates are then bonded with epoxy to the ends of the cylinder, and the specimen is loaded to failure in direct tension. The stress at fracture is determined by dividing the ultimate load by the cross-sectional area of the cylinder to determine the bond strength. If the specimen does not fail at the bond line, the bond strength is considered to be at least the failure stress.

ACI 503R, CSA A23.2-6B, ASTM C 1583, and ICRI Guideline 03739—These test procedures involve coring through a concrete replacement or overlay material into the substrate concrete; adhering with epoxy to a rigid plate or a machined, standard pipe cap with a minimum outside diameter of 50 mm (2 in.) to the core surface; and pulling along the core axis to failure at a rate of approximately 70 to 100 N

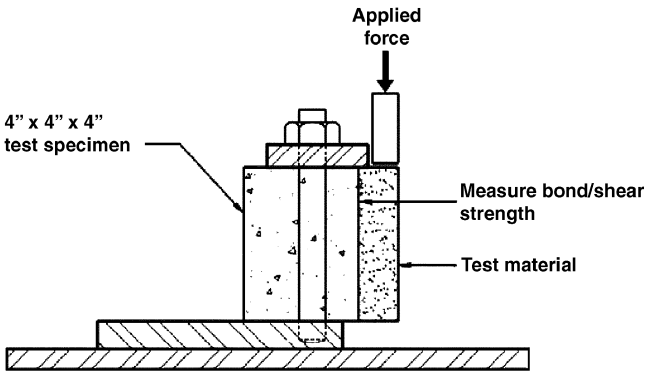


Fig. 2.8—MDOT direct shear bonding test setup.

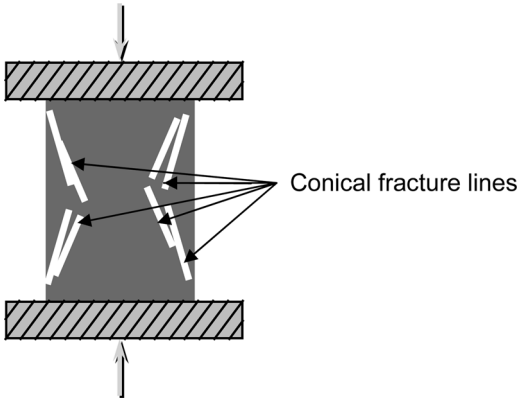


Fig. 2.9—Schematic of compression test setup (ASTM C 39/39M and C 109/109M).

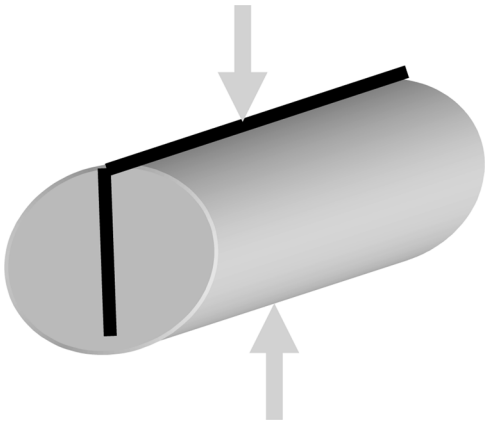


Fig. 2.10—Schematic of splitting tension test setup (ASTM C 307 and C 496/C 496M).

(15 to 23 lb) per second. The procedure is shown schematically in Fig. 2.7. The failure type and load are recorded, and the failure load is reported in terms of MPa (psi).

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

MDOT direct shear bonding test—This direct shear test is performed with a 100 mm (4 in.) cube or a cast or cored cylinder. In the case of the cube specimens, the substrate concrete is cast into a cube, and a 25 mm (1 in.) thick section is sliced off one face. The resulting surface is prepared to create a uniform profile, and the test material is cast onto the substrate to reform a 100 mm (4 in.) cube. The cube is then secured in a test machine and a direct shear force is applied to the bonding surface. The stress at failure is determined by dividing the ultimate load by the area of the bonding surface. A similar procedure is used with a right cylinder. A cored cylinder can be used to test in-place materials. Direct shear bond strengths of 2.1 to 3.4 MPa (300 to 500 psi) are generally considered to be adequate (Knab et al. 1989). The test setup is shown in Fig. 2.8.

2.3.6 *Compressive strength*—Compressive strength is the measured maximum resistance of a material to axial compressive loading, expressed as force per unit cross-sectional area. Two test methods are used to measure compressive strength:

- ASTM C 39/C 39M; and
- ASTM C 109/109M.

Compressive strength is determined by applying an increasing axial compression load until the specimen is unable to support that additional load. The ultimate load is divided by the cross-sectional area to determine the ultimate failure stress (MPa or psi). ASTM C 39/C 39M tests cylindrical concrete specimens; the specimens can vary in size, but 75 x 150 mm (3 x 6 in.), 100 x 200 mm (4 x 8 in.), and 200 x 300 mm (6 x 12 in.) cylinders are most common. ASTM C 109/C 109M tests 50 mm (2 in.) mortar cubes. A schematic of the test setup is shown in Fig. 2.9. Usually, it is desirable to have a compressive strength similar to that of the substrate concrete, but at least 28 MPa (4000 psi).

2.3.7 *Tensile strength*—Tensile strength is the maximum unit stress a material is capable of resisting under axial tension loading. Four test methods are used to measure tensile strength:

- ASTM C 307;
- ASTM C 496;
- CRD-C 164; and
- ASTM C 190 (withdrawn 1990) (discontinued in 1991).

Tensile strength of cementitious materials is usually determined by a splitting tensile test (ASTM C 307 and C 496/C 496M). 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. 2.10. Results are reported in stress (MPa or psi), and are normally of greater magnitude than direct tensile strength measurements (CRD-C 164 and ASTM C 190). Although the ASTM C 190 direct tensile test has been discontinued by ASTM, it is still commonly used in the industry. Direct 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. 2.11.

2.3.8 *Flexural strength and modulus of rupture*—Flexural strength, or modulus of rupture, indicates the ability of a material to resist failure in bending. Five test methods are

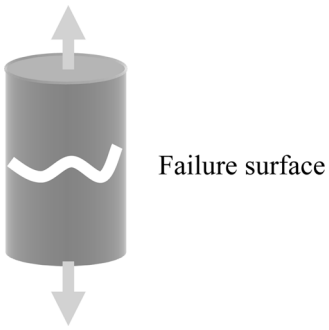


Fig. 2.11—Schematic of direct tension test setup (CRD-C 164 and ASTM C 190/C 190M)

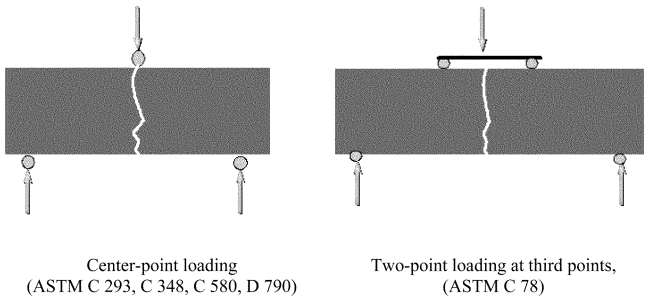


Fig.2.12—Schematics of flexural test setups.

used to measure the flexural strength of different types of repair materials:

- ASTM C 78;
- ASTM C 293;
- ASTM C 348;
- ASTM C 580; and
- ASTM D 790.

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 C 293, C 348, C 580, and D 790) or two loading points (ASTM C 78), as shown schematically in Fig. 2.12. 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 nonuniform material. Tests have shown that the flexural strength from third-point loading may be about 0.52 MPa (75 psi) less than that obtained from center-point loading (PCA 1996). The resulting flexural strength is reported in stress units (MPa, psi).

2.3.9 *Significance of compressive, tensile, and flexural strengths*–The 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 may be beneficial in reducing cracking due to restrained shrinkage and thermal contraction.

2.4—Constructibility characteristics

Constructibility characteristics are those material properties that affect or limit the installation or application of the repair material for various field conditions.

2.4.1 *Cohesiveness*—The cohesiveness of a repair material is its ability to remain intact, or not segregate, during its application. The cohesiveness of the repair material is important for the ease of construction and the uniformity of the repair. For instance, in concrete replacements 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.

2.4.2 *Viscosity*—Viscosity is the resistance to flow exhibited by a material. 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 to penetrate into the concrete pores. Flowable, self-consolidating materials are also available for concrete replacements.

2.4.3 *Environmental considerations*—The 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, the amount of moisture on the surface of the substrate concrete, the relative humidity, the wind speed, whether 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, or the construction conditions should be modified to fit the properties of the repair materials chosen.

2.5—Aesthetic properties

The appearance of repair materials is important in certain circumstances.

2.5.1 *Surface texture*—The surface texture of the repair should generally match that of the adjacent material.

2.5.2 *Color*—The color of the repair should generally match that of the adjacent material, unless the repair is not visible, such as after the application of a coating.

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

2.5.4 *Moisture absorption*—The appearance of the repair material could change when it gets wet, and then change to its original appearance as it dries. The changes in appearance may be different from the adjacent concrete.

2.6—Factors affecting durability

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

2.6.1 *Resistance to freezing and thawing*—Some repair materials, including concrete, are susceptible to deterioration

when exposed to cycles of freezing and thawing in a saturated 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:

- ASTM C 666/C 666M;
- ASTM C 672/C 672M; and
- ASTM C 672/C 672M, as modified by ICRI Guideline 03733 (1996).

Durability of material in freezing environments is evaluated in bulk by ASTM C 666/C 666M or as a surface scaling effect by ASTM C 672/C 672M and modified by ICRI Guideline 03733 (1996). The approach in ASTM C 666/C 666M 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 C 672/C 672M relies on a visual inspection of surface damage caused by freezing-and-thawing cycles of a ponded salt solution, while the ICRI Guideline 03733 modification includes measuring the mass loss.

ASTM C 666/C 666M—This test method includes two different procedures: Procedure A—freezing and thawing in water, and Procedure B—freezing in air and thawing in water. Procedure A is the most commonly used, as the procedure can more easily be automated. A complete test consists of 300 freezing-and-thawing cycles. A durability factor (as generated by the test procedure) 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 C 672/C 672M—This test method, commonly referred to as 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. Test results use a subjective visual scale of 0 to 5, with 0 indicating no scaling, and 5 indicating severe scaling. Refer to Fig. 2.13 for a schematic of the test setup.

ICRI Guideline 03733 (1996) provides a modification of ASTM C 672/C 672M that is often used to eliminate the 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 0.8 kg/m^2 (0.16 lb/ft^2) usually denotes acceptable performance.

The age of the test specimens when initially exposed to the freezing-and-thawing cycling is critical to interpreting the results. ASTM C 672/C 672M has been found to be a very severe test method, and some materials that fail the test may not fail under harsh service conditions. ASTM C 672/C 672M has also been found to be sensitive to surface finishing techniques (Johnston 1993). Conducting the test on a formed face as opposed to the finished face of a specimen can significantly affect the results.

2.6.2 *Permeability*—Permeability is the ability of a material to transmit or resist the penetration of water and water-borne chemicals. The permeability of a repair material is important

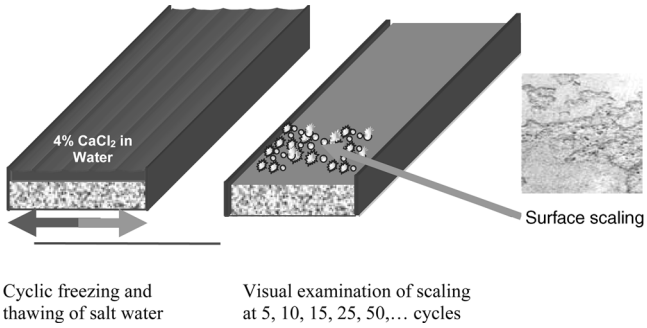


Fig. 2.13—Schematic of ASTM C 672/C 672M freezing-and-thawing test setup.

in environments where the repair material or the 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 age of the specimen at the time of the test.

Four test methods are used to measure permeability:

- AASHTO T 259;
- AASHTO T 277;
- ASTM C 1202; and
- ASTM C 642.

The permeability of concrete or mortar is sometimes determined by its resistance to chloride-ion penetration. AASHTO T 259 consists of ponding a salt solution on the top surface of slab specimens for 90 days and measuring the chloride-ion content at different levels within the concrete. The results can be used to compare different concretes and repair materials. AASHTO T 277 and ASTM C 1202 were developed to provide an indication of a material's resistance to chloride-ion ingress in a shorter period of time, typically 6 hours. In this procedure, a constant voltage is applied across a cylindrical specimen with ionic solutions on both sides of the specimen, and the total electrical current is measured. The test results are influenced by the electrical resistivity of the test material and its permeability. ASTM C 642 is a quick and economical method to approximate the permeable void content of concrete.

AASHTO T 259—A 3% sodium chloride solution is ponded on top of a concrete slab specimen for 90 days, and then the concrete is analyzed to determine the chloride-ion content at different levels below the surface. The findings are reported in percent chloride ions relative to the mass of the concrete or the mass of the cement in the specimen. A schematic of the test setup is shown in Fig. 2.14. AASHTO T 259 requires 90 days to perform, and the results can be used to compare different concretes and repair materials. Care should be taken to ensure that comparative tests are performed in the same manner; in particular, the concrete should be sampled in the same manner for chloride testing, and the same chloride-ion test procedure should be used for all of the samples.

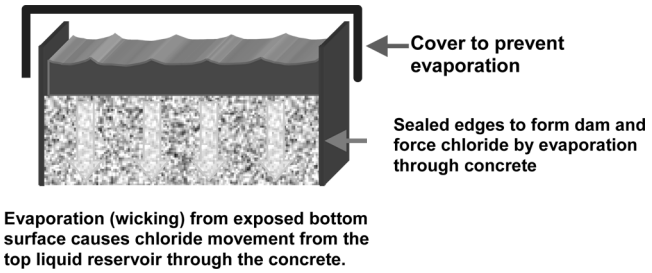
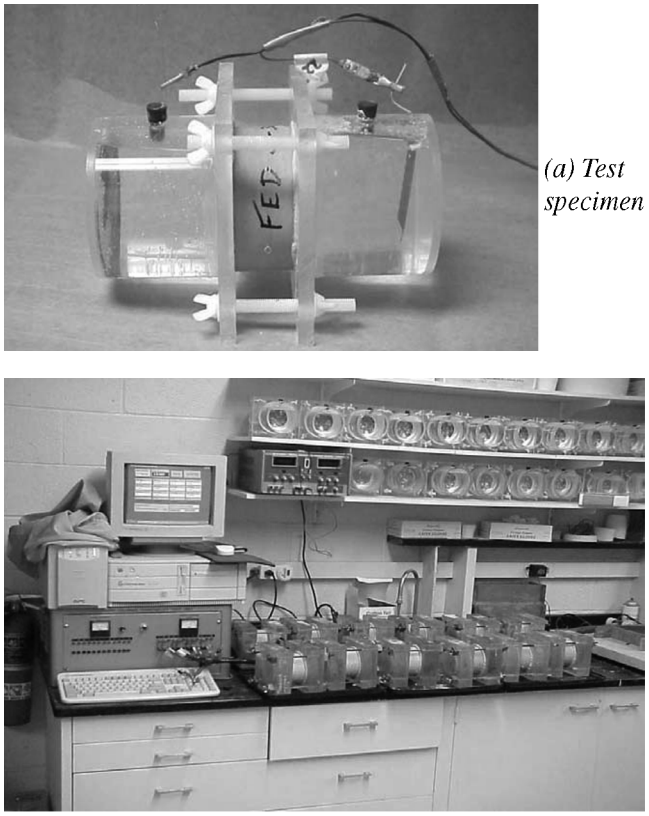


Fig. 2.14—Schematic of AASHTO T 259 test setup.



(a) Test specimen

(b) Test in progress

Fig. 2.15—AASHTO T 277 and ASTM C 1202 rapid chloride permeability test.

AASHTO T 277 and ASTM C 1202—In this procedure, a cylindrical test specimen is placed in the test apparatus with a sodium chloride solution on one side and a sodium hydroxide solution on the other side, as shown in Fig. 2.15(a). A constant voltage is applied across the test specimen for 6 hours, and the total electrical current that is passed is measured. In-progress tests are shown in Fig. 2.15(b). The total charge passed, measured in coulombs, is taken as the measure of the permeability of the material. Generally, moderate water-cementitious material ratio (*w/cm*) concrete (0.4 to 0.5) has values of 2000 to 4000 coulombs; low *w/cm* concrete (less than 0.4) has values ranging from 1000 to 2000 coulombs, and silica fume and polymer-cement concrete have values ranging from 100 to 1000 coulombs (Whiting 1981).

Values obtained from AASHTO T 277 and ASTM C 1202 give an indication of a cementitious material's ability to resist the penetration of chloride ions, but the measured values should be interpreted with caution. Because the electrical current is measured, the electrical resistivity and the permeability of the specimen will influence the test results. These tests are not suitable for testing steel fiber-reinforced concrete or other materials that influence the electrical conductivity of the material. Although the results are reported quantitatively, test values for properly conducted tests on the same material by different laboratories should not differ by more than 51%, according to ASTM C 1202.

ASTM C 642—The absorption after immersion, absorption after immersion and boiling, dry bulk density, bulk density after immersion, bulk density after immersion and boiling, apparent density, and volume of permeable pore space (voids) may be determined by this method. This method may provide an indirect indication of the permeability of cementitious paste repair materials; permeable pore space data from this method, however, should be supplemented by other methods discussed in this section to provide a true indication of permeability. The volume of permeable voids result is affected by the material's porosity and by damage, such as cracking, to applied materials.

2.6.3 *Alkali-aggregate reactions*—Some aggregates are susceptible to deleterious expansive reaction with other components of the repair material, particularly the alkali in the portland cement, or to chemicals introduced by the environment. These aggregates can be identified based on previous service records, or with one or more of the following tests. It is preferable to not use reactive aggregates in environments where deleterious reactions may occur. If such aggregates must be used, steps should be taken to avoid the deleterious reactions, such as modifying the repair material mixture composition or protecting the material from the environment. Protection from the environment can be provided by water-repellent and waterproofing coatings. Eighty percent relative humidity in the concrete has been shown to promote alkali-aggregate reactions (Stark 1991).

Five test methods are used to evaluate alkali-aggregate reactivity potential:

- ASTM C 227;
- ASTM C 1260;
- ASTM C 1293;
- ASTM C 289; and
- ASTM C 295.

ASTM C 227, C 1260, and C 1293 all test the potential for alkali reactivity between a particular aggregate and cement by storing samples of the combined materials in warm, moist conditions and monitoring the change in length over time. Materials with a length change of 0.05% or less are considered to have a high resistance to alkali-silica attack. ASTM C 289 evaluates the reactivity of a particular aggregate by soaking the aggregate in a sodium hydroxide solution. This method may not reliably predict the reactivity in concrete and should not be used. ASTM C 295 describes a petrographic procedure to characterize aggregates, identify aggregate types that are susceptible to alkali-aggregate reaction, and identify other deleterious properties of aggregates that can harm the

concrete. Additional discussion can be found in ACI 221.1R and CSA A864-00.

2.6.4 *Electrical resistivity*—Electrical resistivity is the resistance of a material to the flow of electrical charge in the presence of a voltage potential between two points. Corrosion is an electrochemical process. Therefore, if corrosion of embedded reinforcing steel is a concern, the electrical resistivity of the repair material is important, particularly for concrete replacements. Depending on the method of corrosion protection, a high or low value of this property may be desirable. Cathodic protection systems, both active and passive, generally require a lower value (perhaps about 300 ohms) than the higher resistance value (perhaps 1000 to 15,000 ohms) desired in conventional repairs (ASTM C 1202). Refer to ACI 222R for further guidance. One indication of the resistivity of a repair material can be obtained from AASHTO T 277 or ASTM C 1202, as discussed in Section 2.6.2.

2.6.5 *Abrasion resistance*—Many repairs are subjected to abrasion in service. The abrasion can be from wind-blown debris, mechanical contact, or other sources. In particular, vehicular traffic and abrasion on hydraulic structures are aggressive types of abrasion. Repair materials should have suitable abrasion resistance for their service environment.

Four test methods are used to measure abrasion resistance:

- ASTM C 779/C 779M;
- ASTM C 944;
- ASTM C 418; and
- ASTM C 1138.

ASTM C 779/C 779M and C 944—ASTM C 779/C 779M includes three procedures for determining the relative abrasion resistance of horizontal concrete surfaces, based on depth of wear measurements. The three procedures differ in the type and degree of abrasive force they impart. Procedure A uses revolving disks with No. 60 silicon carbide grit to scour away the concrete in a circular path. Procedure B uses dressing wheels riding in a circular path to peck away the concrete surface. Procedure C uses rapidly rotating ball bearings in a race and under load to impart impact and sliding friction to a wet concrete surface. Depth of wear readings is taken at two intervals: 30 and 60 minutes. The ASTM C 944 test is similar to Procedure B. A test in progress is shown in Fig. 2.16. The tests are intended for use in determining variations in the surface properties of concrete affected by mixture proportions, finishing, and surface treatment. They provide relative results between concretes, but are not intended to provide a quantitative measurement of the service life that may be expected from a specific surface.

ASTM C 418—The abrasion-resistance characteristics of a concrete surface when subjected to the impingement of air-driven silica sand, using specified pressures, abrasive, and sand-blasting equipment, is determined. Wear is determined volumetrically by filling the eroded cavity with a weighed quantity of putty. Comparative data between samples make it possible to rank abrasion resistance but, like the other methods, the prediction of service life is not intended.

ASTM C 1138—The relative resistance of concrete to underwater abrasion is determined by simulating the abrasive action of waterborne particles (silt, sand, gravel, and other solids). The test setup consists of a 300 mm (12 in.) diameter, 100 mm (4 in.) thick test sample immersed 163 mm (6-1/2 in.) under water in a steel pipe. A rotating mixing paddle propels 70 Grade 1000 (Grade 6900) chrome steel grinding balls, graded from 25 to 13 mm (1 to 1/2 in.) in diameter, at the sample surface. The loss in mass after the specified exposure period is used as a measure of abrasion resistance.

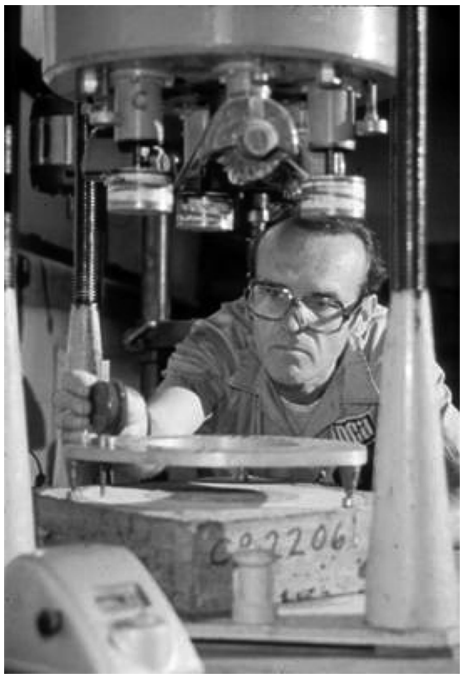


Fig. 2.16—Measuring depth of wear during ASTM C 799/C 779M abrasion test. Note disks (Procedure A) and dressing wheels (Procedure B) at top of machine.

2.6.6 *Resistance to chemical attack*—Repair materials may be exposed to various chemicals in the service environment. The long-term performance of the repair may depend on the proper selection of the repair material and, possibly, on the use of an appropriate protective barrier. In some environments, it may be important that the barrier be free of pinholes and holidays. Some repair materials may be damaged by a solvent-based barrier material. Detailed discussions of resistance to chemical attack can be found in ACI 201.2R and 515.1R and PCA IS001 (2001). In addition, a number of materials and solutions that are aggressive to concrete are listed in PCA IS001 (Portland Cement Association 2001).

Aggressive chemicals can be roughly categorized as sulfates, inorganic and organic acids, alkaline solutions, salt solutions, solvents, and others.

Portland-cement mortar and concrete can degrade when exposed to sulfates in groundwater or elsewhere. ASTM C 1012 evaluates the susceptibility of a cement mortar to sulfate attack by measuring the length change of a specimen over a period of time while exposed to a sodium sulfate solution. The test setup is shown in Fig. 2.17. Results are presented as percent strain at a given time of exposure. A material with a strain of 0.05% or less is considered to have high resistance to sulfate attack.

Table 2.1—Summary of available test methods and test values for concrete replacement materials

Description	Test method	SI units		Inch-pound units		Recommended test
		Typical value—Notes 2 and 4	Recommended value—Note 2	Typical value—Notes 2 and 4	Recommended value—Note 2	
Slant shear bond	ASTM C 882 ASTM C 1042	1 day: 2.8 to 6.9 MPa 7 days: 6.9 to 12 MPa 28 days:14 to 21 MPa	—	1 day: 400 to 1000 psi 7 days:1000 to 1800 psi 28 days:2000 to 3000 psi	—	Note 5
Direct tensile bond	ACI 503R ASTM C 1404/C 1404M CSA A23.2-6B ASTM C 1583 ICRI 03739	1 day: 0.48 to 1.0 MPa 7 days: 1.0 to 1.7 MPa 28 days: 1.7 to 2.1 MPa	Refer to 2.3.5	1 day: 70 to 150 psi 7 days:150 to 250 psi 28 days: 250 to 300 psi	Refer to 2.3.5	Yes
Direct shear bond	MDOT	1 day: 1.0 to 2.1 MPa 7 days: 2.1 to 2.8 MPa 28 days: 2.8 to 4.1 MPa	—	1 day: 150 to 300 psi 7 days: 300 to 400 psi 28 days: 400 to 600 psi	—	Note 6
Length change: concrete (Note 1)	ASTM C 157/C 157M	0.02% (expansion) to –0.05% (shrinkage)	>(–0.05%) (shrinkage)	0.02% (expansion) to –0.05% (shrinkage)	>(–0.05%) (shrinkage)	Note 7
Drying shrinkage: mortar (Note 1)	ASTM C 596	0.05 to 0.15%	<0.10%	0.05 to 0.15%	<0.10%	Yes
Restrained expansion	ASTM C 806	0.06%	Refer to 2.2	0.06%	Refer to 2.2	Yes
Thermal expansion (Note 1)	CRD-C 39	10.8×10^{-6}/°C	Refer to 2.3.3	6×10^{-6}/°F	Refer to 2.3.3	Yes
	ASTM C 531	25×10^{-6}/°C		14×10^{-6}/°F		Yes
	ASTM C 884/C 884M	Qualitative test		Qualitative test		Yes
	ASTM D 696	25×10^{-6}/°C		14×10^{-6}/°F		Yes
Modulus of elasticity	ASTM C 469	6.8 to 38 GPa	Refer to 2.3.2	1 to 5.5 × 10^6 psi	Refer to 2.3.2	Yes
	ASTM C 580	2.1 to 21 GPa		0.3 to 3 × 10^6 psi		Yes
Creep	ASTM C 512	7×10^{-9}/KPa	Refer to 2.3.4	1×10^{-9}/psi	Refer to 2.3.4	Yes
	ASTM C 1181	—		—		Yes
Rapid chloride permeability	ASTM C 1202	28 days: 0 to 5000 Coul.	0 to 3000 Coul.	28 days:0 to 5000 Coul.	0 to 3000 Coul.	Yes
	AASHTO T 277	28 days: 0 to 5000 Coul.	0 to 3000 Coul.	28 days: 0 to 5000 Coul.	0 to 3000 Coul.	Yes
90-day ponding	AASHTO T 259	0.42% at 13 mm 0.15% at 25 mm	—	0.42% at 0.5 in. 0.15% at 1.0 in.	—	Yes
Absorption after immersion	ASTM C 642	4 to 6%	<6%	4 to 6%	<6%	Yes
Volume of permeable pore space	ASTM C 642	5 to 12%	<12%	5 to 12%	<12%	Note 3
Freezing-and-thawing resistance (Note 1)	ASTM C 666/C 666M	28 days: 80 to 100 DF at 300 cycles	>80 DF	28 days: 80 to 100 DF at 300 cycles	>80 DF	Yes
Scaling resistance	ASTM C 672/C 672M	28 days: 0 to 5 visual rating at 50 to 300 cycles	<2	28 days: 0 to 5 visual rating at 50 to 300 cycles	< 2	Yes
Sulfate resistance	ASTM C 1012	0 to 0.2%	<0.1%	0 to 0.2%	<0.1%	Yes
Alkali-aggregate reaction	ASTM C 227	Refer to 2.6.3	<0.1%	Refer to 2.6.3	<0.1%	Yes
	ASTM C 289	Qualitative test	Refer to 2.6.3	Qualitative test	Refer to 2.6.3	Note 8
	ASTM C 295	Refer to 2.6.3	Refer to 2.6.3	Refer to 2.6.3	Refer to 2.6.3	Yes
	ASTM C 1260	Refer to 2.6.3	<0.1%	Refer to 2.6.3	<0.1%	Yes
	ASTM C 1293	Refer to 2.6.3	<0.1%	Refer to 2.6.3	<0.1%	Yes
Abrasion resistance	ASTM C 779/C 779M Procedure A	0.1 to 2.5 mm at 30 min. 0.2 to 5.1 mm at 60 min.	Refer to 2.6.5	0.004 to 0.1 in. at 30 min. 0.008 to 0.2 in. at 60 min.	Refer to 2.6.5	Refer to 2.6.5
Tensile strength (Note 1)	ASTM C 496	2.8 to 12 MPa	>2.8 MPa	400 to 1800 psi	>400 psi	Yes
	CRD-C 164	1.4 to 4.1 MPa	>2.8 MPa	200 to 600 psi	>400 psi	Note 3
	ASTM C 307	—	—	—	—	Yes
Flexural strength (Note 1)	ASTM C 78	28 days: 8.3 MPa	—	28 days: 1200 psi	—	Yes
	ASTM C 348	28 days: 10 MPa		28 days: 1500 psi		Yes
	ASTM C 580	7 days: 17 MPa		7 days: 2400 psi		Yes
	ASTM C 293	28 days: 3.4 to 8.3 MPa		28 days: 500 to 1200 psi		Yes
Compressive strength (Note 1)	ASTM C 109/C 109M	28 days: 28 to 85 MPa	Similar to substrate	28 days: 4000 to 12,000 psi	Similar to substrate	Yes
	ASTM C 39/C 39M	28 days: 21 to 70 MPa		28 days: 3000 to 10,000 psi		Yes

Note 1: Materials properties indicated in the description column have a specific modification to test method discussed in text of this chapter.
Note 2: Typical and recommended test values are for portland-cement concrete. Recommended values are minimum values by ACI Committee 546 for typical repair materials used in successful repairs and are not necessarily applicable for all conditions.
Note 3: Test indicated in the recommended test column do not have a recommendation from ACI Committee 546.
Note 4: MPa rounded to two significant digits.
Note 5: No; results highly dependent on compressive strength of substrate and roughness of bonding surface.
Note 6: No; test apparatus not commonly available and test not commonly performed.
Note 7: No; curing and comparator reading regimens not representative of field conditions of repair mortars and concretes.
Note 8: No; may not reliably predict aggregate activity in concrete.

Table 2.2—Summary of available test methods and test values for crack repair materials*

Description	Test method	Specimen age	SI units		Inch pound units		Recommended test
			Typical value	Recommended value	Typical value	Recommended value	
Epoxy resin							
Slant shear bond	ASTM C 882	14 days	6.9 to 21 MPa	>10 MPa	1000 to 3000 psi	>1500 psi	Yes
Tensile strength	ASTM D 638	7 days	28 to 55 MPa	>35 MPa	4000 to 8000 psi	>5000 psi	Yes
Elongation at break	ASTM D 638	7 days	1 to 10%	1 to 10%	1 to 10%	1 to 10%	Yes
Modulus of elasticity	ASTM D 638	14 days	1.4 to 4.1 GPa	2.1 to 3.4 GPa	2 to 6 × 10^5 psi	3 to 5 × 10^5 psi	Yes
Deflection temperature	ASTM D 648	7 days	43 to 71 °C	>49 °C	110 to 160 °F	>120 °F	Yes
Flexural strength	ASTM D 790	14 days	35 to 105 MPa	>6.9 MPa	5000 to 15,000 psi	>1000 psi	Yes
Compressive strength	ASTM D 695	7 days	35 to 105 MPa	>21 MPa	5000 to 15,000 psi	>3000 psi	Yes
Compressive modulus	ASTM D 695	7 days	0.52 to 3.4 GPa	>1.0 GPa	75,000 to 500,000 psi	>150,000 psi	Yes
Shear strength	ASTM D 732	14 days	17 to 70 MPa	>14 MPa	2500 to 10,000 psi	>2,000 psi	Yes
Gel time	ASTM C 881	—	5 min. to 3 hours	>30 minutes	5 minutes to 3 hours	>30 minutes	Yes
Water absorption	ASTM D 570	24 hours	0.25 to 1.5%	<1%	0.25 to 1.5%	<1%	Yes
Coefficient linear shrinkage	ASTM D 2566	—	0.002 to 0.01	<0.005	0.002 to 0.01	<0.005	Yes
Viscosity	ASTM D 2393	Immediately	50 to 2000 cP	<1000 cP	50 to 2000 cP	<1000 cP	Yes
High-molecular-weight methacrylate							
Slant shear bond	ASTM C 882	14 days	6.9 to 21 MPa	>10 MPa	1000 to 3000 psi	>1500 psi	Yes
Compressive strength	ASTM D 695	7 days	21 to 70 MPa	>21 MPa	3000 to 10,000 psi	>3000 psi	Yes
Viscosity	ASTM D 2393	Immediately	20 to 200 cP	<100 cP	20 to 200 cP	<100 cP	Yes
Gel time	ASTM C 881	—	5 minutes to 1 hour	>10 minutes	5 minutes to 1 hour	>10 minutes	Yes
Polyurethane chemical grout							
Shear strength	ASTM C 273	—	—	—	—	—	Note 1
Tensile strength	ASTM D 1623	—	—	—	—	—	Note 1
Elongation	ASTM D 1623	14 days	25 to 400%	>15%	25 to 400%	>15%	Yes
Shrinkage	ASTM D 2126	14 days	0 to 10%	<1%	0 to 10%	<1%	Yes
Polyurethane sealant							
Adhesion in peel (concrete)	ASTM C 794	21 days	22 to 180 N	>22 N	5 to 40 lb	>5 lb	Yes
Tensile strength	ASTM D 412	21 days	0.69 to 1.7 MPa	0.69 to 1.7 MPa	100 to 250 psi	100 to 250 psi	Note 2
Elongation at break	ASTM D 412	21 days	400 to 800%	>400%	400 to 800%	>400%	Yes
Shore A hardness	ASTM C 661	21 days	15 to 50%	15 to 50%	15 to 50%	15 to 50%	Yes
(Joint movement)	ASTM C 719	21 days	12.5 to 25%	12.5 to 25%	12.5 to 25%	12.5 to 25%	Yes
Tack-free time	ASTM C 679	N/A	7 to 24 hours	<72 hours	7 to 24 hours	<72 hours	Yes
Artificial weathering and staining	ASTM C 510	21 days	500 to 2000 hours	>100 hours	500 to 2000 hours	>100 hours	Yes
Tear strength	ASTM D 624	21 days	8.8 to 18 N/mm	8.8 to 18 N/mm	50 to 100 lb/in.	50 to 100 lb/in.	Yes
Silicone sealant							
Adhesion in peel (concrete)	ASTM C 794	21 days	2.3 to 11 kg	>2.3 kg	5 to 25 lb	>5 lb	Yes
Tensile strength	ASTM D 412	21 days	0.69 to 2.1 MPa	0.69 to 2.1 MPa	100 to 300 psi	100 to 300 psi	Note 2
Elongation at break	ASTM D 412	21 days	400 to 1000%	>400%	400 to 1000%	>400%	Yes
Shore A hardness	ASTM C 661	21 days	5 to 15	5 to 15	5 to 15	5 to 15	Yes
Joint movement	ASTM C 719	21 days	50 to 100%	50 to 100%	50 to 100%	50 to 100%	Yes
Tack free	ASTM C 679	—	1 to 2 hours	<72 hours	1 to 2 hours	<72 hours	Yes
Artificial weathering and staining	ASTM C 510	21 days	500 to 2000 hours	>100 hours	500 to 2000 hours	>100 hours	Yes
Tear strength	ASTM D 624	21 days	0.36 to 0.71 kg/mm	>0.89 kg/mm	20 to 40 lb/in.	>50 lb/in.	Yes
Polymer grout (for crack and shallow concrete replacements)			Consider 3.5 to 7.0 N/mm	8.8 N/mm			
Slant shear bond	ASTM C 882	14 days	6.9 to 21 MPa	>10 MPa	1000 to 3000 psi	>1500 psi	Yes
Tensile strength	ASTM D 638	14 days	3.4 to 10 MPa	>5.2 MPa	500 to 1500 psi	>750 psi	Yes
Modulus of elasticity	ASTM D 638	14 days	1.4 to 6.9 GPa	1.4 to 6.9 GPa	2 to 10 × 10^5 psi	2 to 10 × 10^5 psi	Yes
Deflection temperature	ASTM D 648	7 days	43 to 71 °C	>49 °C	110 to 160 °F	>120 °F	Yes
Flexural strength	ASTM D 790	14 days	14 to 35 MPa	>6.9 MPa	2000 to 5000 psi	>1000 psi	Yes
Compressive strength	ASTM D 695	7 days	21 to 85 MPa	>21 MPa	3000 to 12,000 psi	>3000 psi	Yes
Compressive modulus	ASTM D 695	7 days	0.69 to 6.9 GPa	>1.0 GPa	100,000 to 1,000,000 psi	>150,000 psi	Yes
Shear strength	ASTM D 732	14 days	14 to 35 MPa	>14 MPa	2000 to 5000 psi	> 2000 psi	Yes
Gel time	ASTM C 881	Immediately	5 minutes to 3 hours	>30 minutes	5 minutes to 3 hours	>30 minutes	Yes
Thermal expansion	ASTM C 531	—	4.1 to 5.1 × 10^{-5}/°C	Note 3	2.3 to 2.8 × 10^{-5}/°F	Note 3	Yes

Table 2.2 (cont.)—Summary of available test methods and test values for crack repair materials*

Description	Test method	Specimen age	SI units		Inch-pound units		Recommended test
			Typical value	Recommended value	Typical value	Recommended value	
Polymer-cement grout							
Bond strength	ASTM C 1042	28 days	10 to 21 MPa	>10 MPa	1500 to 3000 psi	>1500 psi	Yes
Direct tensile bond	ACI 503R	28 days	0.69 to 2.1 MPa	>0.86 MPa	100 to 300 psi	>125 psi	Yes
Tensile strength	ASTM C 496/C 496M	28 days	2.1 to 6.9 MPa	>2.1 MPa	300 to 1000 psi	>300 psi	Yes
Modulus of elasticity	ASTM C 469	28 days	6.9 to 38 GPa	—	1 to 5.5 × 10^6 psi	—	Yes
Thermal expansion	ASTM C 531	28 days	1.37 to 6.4 × 10^{-5}/°C	—	3 to 14 × 10^{-6}/°F	—	Yes
Drying shrinkage	ASTM C 596	28 days	0.05 to 0.15%	<0.10%	0.05 to 0.15%	<0.10%	Yes
Flexural strength	ASTM C 293	28 days	8.3 MPa	>3.4 MPa	1200 psi	>500 psi	Yes
Compressive strength	ASTM C 109/C 109M	28 days	28 to 85 MPa	>20.7 MPa	4000 to 12,000 psi	>3000 psi	Yes
Cementitious grout							
Bond strength	ASTM C 882	28 days	10 to 21 MPa	>10.3 MPa	1500 to 3000 psi	>1500 psi	Yes
Direct tensile bond	ACI 503R	28 days	0.69 to 2.1 MPa	>0.87 MPa	100 to 300 psi	>125 psi	Yes
Tensile strength	ASTM C 496/C 496M	28 days	2.1 to 6.9 MPa	>2.1 MPa	300 to 1000 psi	>300 psi	Yes
Modulus of elasticity	ASTM C 469	28 days	6.9 to 38 GPa	—	1 to 5.5 × 10^6 psi	—	Yes
Thermal expansion	ASTM C 531	28 days	0.137 to 0.64 × 10^{-6}/°C	—	3 to 14 × 10^{-6}/°F	—	Yes
Drying shrinkage	ASTM C 596	28 days	0.05 to 0.15%	<0.10%	0.05 to 0.15%	<0.10%	Yes
Compressive strength	ASTM C 109/C 109M	28 days	28 to 85 MPa	>21 MPa	4000 to 12,000 psi	>3000 psi	Yes
Strip-and-seal system							
Sheeting							
Tensile strength	ASTM D 412	—	6.9 MPa	—	1000 psi	—	Note 1
Elongation at break	ASTM D 412	—	800%	—	800%	—	Note 1
Tear resistance	ASTM D 624	—	44.6 kg/cm	—	250 lb/in.	—	Note 1
Adhesive							
Slant shear bond	ASTM C 882	14 days	6.9 to 21 MPa	>10 MPa	1000 to 3000 psi	>1500 psi	Yes
Tensile strength	ASTM D 638	7 days	14 to 35 MPa	>14 MPa	2000 to 5000 psi	>2000 psi	Yes
Elongation at break	ASTM D 638	7 days	0.1 to 1%	>0.25%	0.1 to 1%	>0.25%	Yes
Modulus of elasticity	ASTM D 638	14 days	1.4 to 6.9 GPa	1.4 to 6.9 GPa	2 to 10 × 10^5 psi	2 to 10 × 10^5 psi	Yes
Deflection temperature	ASTM D 648	7 days	43 to 71 °C	>49 °C	110 to 160 °F	>120 °F	Yes
Flexural strength	ASTM D 790	14 days	14 to 35 MPa	>6.9 MPa	2000 to 5000 psi	>1000 psi	Yes
Compressive strength	ASTM D 695	7 days	35 to 105 MPa	>21 MPa	5000 to 15,000 psi	>3000 psi	Yes
Shear strength	ASTM D 732	14 days	14 to 35 MPa	>14 MPa	2000 to 5000 psi	>2000 psi	Yes
Gel time	ASTM C 881	—	20 to 60 minutes	>30 minutes	20 to 60 minutes	>30 minutes	Yes
Water absorption	ASTM D 570	24 hours	0.25 to 1.5%	< 1%	0.25 to 1.5%	<1%	Yes
System							
Peel strength	ASTM D 903	7 days	No loss of adhesion	—	No loss of adhesion	—	Note 1

*Materials tested at 20 °C unless noted otherwise.
Note 1. Tests indicated in recommended test column do not have recommendation from ACI Committee 546.
Note 2. This is not a key user characteristic, but is a fast test used for product development.
Note 3. Make as similar to substrate as possible by selecting appropriate formulation and adding aggregates.

Acids (materials with a pH below 7) react with concrete and cement-based repair materials to form compounds that are water-soluble. Acids may also attack carbonate aggregates (limestone and dolomite). The effect of an acid is influenced not only by its concentration, but also by the chemical type, the length of exposure, and the temperature.

Alkaline solutions (materials with a pH above 7) are less aggressive than acids to portland cement-based materials, but may react with other types of repair materials, depending on concentration, chemical type, temperature, and the chemical composition of the repair material. Hydrated cement is alkaline, so most repair materials have at least some resistance to high-pH environments. Strong concentrations of sodium or potassium alkalis may induce alkali-silica reactions if susceptible aggregates are present.

Salt solutions may be slightly acidic or alkaline and, depending on the chemical composition, may attack concrete and concrete repair materials. Salt scaling is one form of chemical attack (Taylor 1990).

Some solvents are aggressive to polymeric materials and some may slowly attack concrete. A more common problem is solvent penetration into the substrate concrete, which can adversely affect the bond of the repair material.

Other chemicals can be aggressive to both the concrete and repair materials. Extremely soft or purified water can slowly leach the calcium from cement-based concrete and mortar.

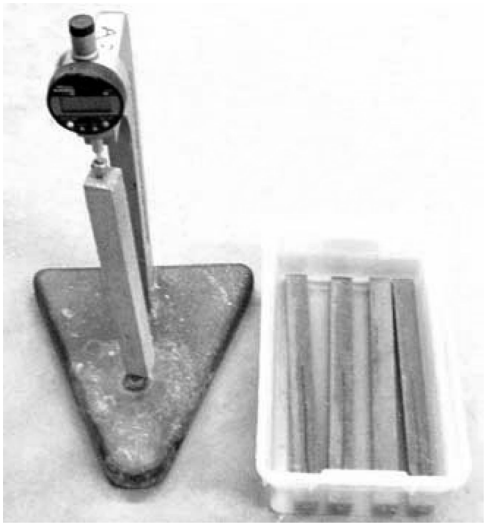


Fig. 2.17—Specimens soaking in sodium sulfate solution (right), and length measurement (left), during ASTM C 1012 test.

2.7—Chemical composition

2.7.1 *Repair material chemistry*—It is sometimes advisable for repair products to be independently tested for comparison with competitive products, for product approval purposes, or to ensure that the chemical formulation remains the same in the future.

2.8—Summary tables

Table 2.1 presents a general summary of the test procedures described in this chapter, including, in some cases, typical test values. The test values are for portland-cement concrete. ACI 503R, 548.1R, and 548.3R can be referred to for information on polymer-modified and polymer concrete replacement materials. Because Table 2.1 is a summary, it is necessarily brief. The text of the chapter should be referred to for further information.

Table 2.2 presents a summary of test procedures for crack repair materials, including, in some cases, typical test values. The test methods are, in general, not discussed in the text of Chapter 2, but the various material properties are part of the Chapter 3 discussion of crack repair material selection. ACI 224.1R, 504R, and 503.5R can be referred to for information on crack repair materials.

Where recommended test values are listed in Tables 2.1 and 2.2, they represent the minimum values recommended by Committee 546 for typical repair materials used in successful repairs, and are not necessarily applicable for all conditions. For most of the tests, Committee 546 has indicated if the test is recommended for evaluating repair materials. Some of the recommended test methods listed in the tables are not appropriate for certain repair materials or repair applications; some are useful for comparing different materials.

CHAPTER 3—REPAIR MATERIAL SELECTION

Each repair application places different demands on the repair materials, and the repair materials should have suitable properties to meet these demands throughout the intended life of the repair. All repair materials have limitations, and the material specifier and user should select the materials with the best chance of good performance. Tables 2.1 and 2.2 provide a summary of the test methods available for comparing the properties of repair and other materials. Material cost is often the deciding factor between comparable materials. While life-cycle cost is a better comparator between alternate repair materials, life-cycle costs are often not available or are approximate at best, and the repair specifier is left with a choice based on the initial cost of the materials and their application for materials with anticipated similar durability.

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 not available to the specifier, except possibly in general terms. Previous 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, such as surface and crack repair materials. These lists can provide independent evaluations of such products. Because repair products may be reformulated and their physical properties altered over time, some DOTs, such as Alberta Transportation, AB, Canada, periodically update their approval lists based on regular retesting. AASHTO provides a bulletin board for State DOTs to voluntarily report the findings of product testing.

Before any repairs are undertaken, it is essential to follow the steps of assessment discussed in Chapter 1 to achieve the desired outcome.

The repair types and the associated repair materials are presented in the following categories:

- Concrete replacements and overlays; and
- Crack repairs.

3.1—Concrete replacements and overlays

3.1.1 *Materials*—The materials most commonly used for concrete replacements and overlays are based on hydraulic binders such as:

- Portland or blended cement-based concrete;
- Portland or blended cement-based silica-fume-enhanced concrete, fiber-enhanced concrete, or both (silica-fume concrete, fiber-reinforced concrete);
- Portland or blended cement-based polymer-cement concrete (polymer-cement concrete);
- Magnesium-ammonium-phosphate-cement concrete (MAPCC);
- Polymer-based concrete (polymer concrete);
- Portland or blended cement-based mortar (cement mortar);
- Portland or blended cement-based, silica fume-enhanced mortar, fiber-enhanced mortar, or both (silica fume mortar, fiber-reinforced mortar);
- Portland or blended cement-based, polymer-cement mortar (polymer-cement mortar);
- Magnesium-ammonium-phosphate-cement mortar (MAPCM); and
- Polymer-based mortar (polymer mortar).

3.1.1.1 *Concrete*—Concrete 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 the concrete. Pozzolanic materials, such as some fly ashes, may be used in conjunction with portland cement for economy or to provide specific properties such as reduced early heat of hydration, improved later-age strength development and reduced permeability, or increased resistance to alkali-aggregate reaction and sulfate attack.

Concrete proportions should be carefully selected to provide the necessary characteristics for the particular application, such as workability, weight, strength, and durability, that is, resistance to deterioration under the expected exposure conditions (ACI 211.1). To minimize drying shrinkage, the repair concrete should have a water content as low as possible, the smallest paste volume and the largest size coarse aggregates that are feasible, and a coarse aggregate content as high as possible. Shrinkage-reducing admixtures or shrinkage-compensating cements may also be considered when proportioning a concrete mixture. According to ACI 201.2R, frost-resistant, air-entrained, normalweight concrete should have a maximum *w*/*cm* of 0.45 for thin sections and 0.50 for all other structures. Mixing, transporting, placing, and curing should follow the guidance of ACI 304R, ACI 304.1R, ACI 304.2R, ACI 304.5R, ACI 304.6R, and ACI 308R.

Many properties of concrete (when used as a repair material), such as modulus of elasticity and coefficient of thermal expansion, are typically of similar magnitude to those of the substrate concrete. Entrained air can be incorporated into the repair concrete to provide freezing-and-thawing resistance. The quality of the 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 a high-range water-reducing admixture. This type of concrete is called low *w*/*cm* concrete.

Typically, a concrete or mortar repair will attempt to contract as a result of shrinkage, cooling, and autogeneous 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, aesthetic objections, and other factors as discussed elsewhere in this document. Drying shrinkage can be minimized with appropriate mixture proportioning, such as maximizing the size of coarse aggregates compatible with the depth of the application, and plastic shrinkage cracking can be minimized with proper curing. Some admixtures, such as accelerating admixtures, may increase the repair material shrinkage and the resulting cracking. While properly proportioned concrete has good durability, some other repair materials, such as polymer concrete and magnesium-ammonium-phosphate concrete, are more resistant to chemical attack.

3.1.1.2 *Silica-fume concrete*—Silica fume, a by-product of the ferrosilicon industry, is highly pozzolonic material that is used to enhance mechanical and durability properties of concrete. Silica-fume concrete is conventional concrete with silica fume and a high-range water-reducing admixture added. Typical silica fume dosage ranges from 5 to 10% by weight of cement.

Silica-fume concrete has properties similar to but is generally stronger than conventional concrete, and because of the increased strength, it usually has higher bond strength than comparable conventional concrete. 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 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, it is more susceptible to plastic shrinkage cracking than concrete with a moderate *w*/*cm*. The potential for cracking of restrained concrete repairs, with and without silica fume, should be recognized. Any variations in concrete materials, mixture proportions, and construction practices that will 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).

3.1.1.3 *Polymer-cement concrete*—Polymer-cement concrete 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.

Compared with conventional concrete, polymer-cement concrete has increased flexural and bond strength, reduced permeability, and provides increased protection against corrosion of embedded reinforcement (Mindness and Young 1981). Polymer-cement concrete is more difficult to place and finish than conventional concrete, and has a relatively short working time of 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 aforementioned constructibility limitations (ACI 548.1R).

Because of the short working time, polymer-cement materials should be batched and mixed on site. When a concrete mixer is used on small repairs, batch sizes should be restricted to those quantities that can be placed and finished

within the working time. A longer mixing time may result in a marked increase in the total air content, which can result in a significant reduction in the compressive strength. The manufacturer may or may not add a defoaming agent to the polymer and, thus, the manufacturer should be consulted for the recommended mixing procedures and times. Continuous mixers are typically used where large quantities of polymer-cement concrete are required. It is recommended that air content tests be performed.

Polymer-cement concrete is normally moist-cured for 1 to 2 days and then air-dried. While the drying shrinkage of concrete is not increased by the addition of polymers, polymer-cement concrete is more sensitive to plastic shrinkage if not properly cured. Concrete modified with styrene butadiene or some epoxies will exhibit a color change when exposed to UV light (ACI 548.1R and 548.3R).

3.1.1.4 *Magnesium-ammonium-phosphate-cement concrete (MAPCC)*—MAPCC is concrete in which magnesium-ammonium-phosphate is substituted for the portland or blended cement. It has excellent bond, low drying shrinkage, rapid strength gain, and low permeability (Popovics and Rajendran 1987; Popovics et al. 1987).

Because the binder is not based on portland cement, the surface preparation, application, and curing requirements are different. MAPCC should not be applied over a carbonated substrate (that is, a pH no lower than 10) because low bond strength may result. (The pH should be tested before application.) MAPCC hardens rapidly and generates ammonia and large quantities 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. The 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.

MAPCC is used for specialized applications. The rapid strength gain and volume stability make this repair material a good option for fast turnaround applications and for long, slender repairs. Typically, the drying shrinkage of MAPCC is less than that of other rapid-setting repair materials. The specifier and user should consult with the material manufacturer for the specific material properties to determine the applicability and use of the material.

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

Polymer concrete may have low shrinkage as it cures, good bond strength to the substrate concrete, high tensile and flexural strength, low permeability, increased protection against corrosion of embedded reinforcing steel, and good resistance to chemical attack (ACI 548.1R). 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).

The cure time of polymer concrete is directly related to the polymer and other agents that are used, the concrete substrate temperature, the air temperature, and the temperature that is 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 is not controlled, the aggregates in the polymer concrete mixture should be carefully graded and proportioned to minimize the distance between the aggregate particles. 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; however, this may also make this material inappropriate for structural repairs.

Most polymers used in polymer concrete soften when heated. Their mechanical properties change significantly beyond their heat deflection temperatures (HDT). The HDT is different for each formulation, but for those systems used in concrete construction, it generally ranges from 16 to 71 °C (60 to 160 °F). Some polymers may not properly cure at higher temperatures, and may fail in fires (ACI 503R). Solvents in surface coatings and sealers may soften the polymer concrete.

General construction workers usually are not experienced in working with polymer concrete, and 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 requiring 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 503R and 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.

3.1.1.6 *Cement mortar*—Cement mortar consists of portland cement, fine aggregate, and water. Cement mortar is frequently mixed in small batches at the site; therefore, it may be difficult to maintain uniform characteristics. Because of the absence of coarse aggregate, higher water volume, higher cement content, and the higher paste-aggregate ratio, cement mortar shrinks more than concrete, often resulting in more cracking, and further repair may be needed. Water-

reducing admixtures, 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).

Prepackaged repair mortars are also commercially available. Cement, fine aggregate, dry admixtures, and, frequently, proprietary ingredients are blended in a production plant and then packaged into virtually any size of container. Prepackaged materials may offer more consistent and predictable work-site performance. Additional potential advantages include, but are not limited to:

- Better mixture and quality control at the work site. Commonly, only water is added at the work site;
- Quality control. 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 the International Organizations for Standards (ISO), which means that their production processes and procedures are documented and consistent with this documentation. It should be noted, however, that ISO certification means that a product is produced consistently, but does not imply that it is a good product;
- Performance-based materials. 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;
- Data readily available. 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; and
- Some mixtures can be extended with coarse aggregate to create concrete for repairing deeper sections. The extended mixtures will have properties more similar to concrete rather than to mortar.

These prepackaged materials have a limited shelf life and generally should not be used after the expiration of this limit.

3.1.1.7 *Silica-fume mortar*—Silica-fume mortar is cement mortar with silica fume added. The silica fume increases the bond strength and cohesiveness of the mortar. Silica-fume mortar also has increased compressive and tensile strength, reduced permeability, and increased electrical resistivity characteristics. It is also more resistant to chemical attack. Again, the absence of coarse aggregate causes increased shrinkage and greater tendency to crack.

The potential advantages outlined in Section 3.1.1.6 resulting from the use of prepackaged materials apply, plus the benefits associated with the incorporation of silica fume into a repair mortar. Site-added silica fume may be difficult to adequately disperse.

3.1.1.8 *Polymer-cement mortar*—Polymer-cement mortar consists of cement mortar with a polymer modifier added. Compared with cement mortar, polymer-cement mortar has excellent bond strength and cohesiveness, improved resistance to freezing and thawing, reduced permeability, increased electrical resistivity, and improved resistance to chemical attack. As with any mortar, increased shrinkage and cracking should be expected because of the absence of coarse aggregate and higher water and cement contents. Refer to Section 3.1.1.3 for further discussion of the effects of using a polymer modifier.

Prepackaged repair mortars that contain a dry polymer are widely used. The potential advantages of prepackaged materials are discussed in Section 3.1.1.6.

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

3.1.1.9 *Magnesium-ammonium-phosphate-cement mortar (MAPCM)*—MAPCM is mortar in which magnesium-ammonium-phosphate cement is completely substituted for portland cement. It is used for specialized repairs such as those requiring very rapid strength development, low shrinkage, application in below-freezing conditions, or very high bond strength. Refer to Section 3.1.1.4 for further discussion of the use of MAPCM.

3.1.1.10 *Polymer mortar*—Polymer mortar consists of a polymer binder and fine aggregate. Polymer mortar has acceptable bond cohesiveness; good volume stability; relatively high compressive and tensile strengths; acceptable resistance to freezing and thawing; low permeability; high electrical resistivity; and high chemical resistance characteristics. 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 that are used, as well as the concrete substrate temperature, the air temperature, and the temperature that is attained by the mixed polymer. While polymer mortar generally sets much more quickly than hydraulic 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 the substrate concrete, due to high exotherm of some polymer compositions, external temperature variations, and differences in the 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 become plastic when heated, and hard when cooled. Their mechanical properties change significantly beyond their HDTs. The HDT is different for each formulation, but for those systems used in concrete construction, it generally ranges from 16 to 71 °C

(60 to 160 ºF). Some polymers may not cure at a higher temperature, and may soften in fire (ACI 503R).

Construction workers are usually not experienced in working with polymer mortar, and require special training. Moisture in the aggregate or on the substrate concrete surface adversely affects most polymer mortars. Special clean-up solvents are necessary. Special safety equipment and precautions may be necessary due to fumes and flammability of some materials. Polymer mortar does not usually blend in with the appearance of the adjacent existing concrete.

3.1.2 *Types of concrete replacements and overlays*—Based on typical repair thicknesses and common methods for applying these materials, the following sections on concrete replacements and overlays are divided into three categories: deep concrete replacements (including full-depth replacement) and overlays, shallow concrete replacements and overlays, and thin overlays. For the purposes of distinguishing repair materials in this guide, deep concrete replacements and overlays are thicker than 19 to 25 mm (3/4 to 1 in.), and the repair materials include fine and coarse aggregate; shallow concrete replacements and overlays are at least 1.6 to 3.2 mm (1/16 to 1/8 in.) thick and less than 19 to 25 mm (3/4 to 1 in.) thick, and the repair materials include fine aggregate only; and thin overlays are essentially thick coatings less than 1.6 to 3.2 mm (1/16 to 1/8 in.) thick. Table 3.1 provides a listing of the materials that are commonly used for each repair category, along with a summary of the favorable and unfavorable properties of the various materials relative to repair categories.

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, proprietary materials, or applying a surface treatment should be considered.

3.1.3 *Deep concrete replacements and overlays*—Deep concrete replacements and overlays, defined for the purposes of this guide as thicker than 19 to 25 mm (3/4 to 1 in.), are commonly constructed with repair materials that include fine and coarse aggregates. For deep concrete replacements and overlays, top surface (horizontal) applications have different requirements from overhead and vertical applications, and are discussed separately in the following sections.

3.1.3.1 *Top surface (horizontal) applications*—Materials used for deep concrete replacements and overlays in top surface applications include concrete, silica-fume concrete, polymer-cement concrete, MAPCC, and polymer concrete (Table 3.1). Concrete 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 for concrete replacements in applications where its enhanced properties are desirable. Polymer-cement concrete is used for protective overlays and, less frequently, for concrete replacements due to its higher cost. MAPCC is used for concrete replacements in situations where its cost premium is offset by special repair requirements, such as minimum downtime. Polymer concrete is used for concrete replacements and overlays in situations where its cost premium is offset by special repair requirements, such as minimum downtime or resistance to chemical attack.

3.1.3.2 *Vertical and overhead applications*—For vertical and overhead applications, two primary concerns for repairs that are not formed are adherence to the substrate and cohesiveness of the repair material during application and curing of the repair material, to resist the pull of gravity. Also, vertical and overhead concrete replacements are commonly not exposed to as aggressive an in-service environment as top surface replacements, so the durability properties of concrete replacements are often not as critical. An exception is in environments where reactive gasses, chemicals, and high humidity or water are present, such as in wastewater treatment plants, chemical plants, and pulp and paper mills. Refer to Section 3.1.6 for a further discussion of repairs in aggressive environments. Frequently, repair materials with improved bond are high-quality materials with improved durability characteristics as well.

A distinguishing characteristic of the repair is the construction method. Common construction methods are form-and-cast, preplaced aggregate, high-velocity placement with pneumatic pressure (shotcrete), and trowel-applied, which are discussed in the following sections.

3.1.3.2.1 *Form-and-cast repairs*—In form-and-cast repairs, the repair area is formed and the repair material is placed by gravity flow or pumping through an opening in the form or through a hole in the substrate concrete. Materials used for form-and-cast repairs include concrete, silica-fume concrete, polymer-cement concrete, and polymer concrete (Table 3.1). Again, concrete is often used, particularly for vertical concrete replacements where less resistance to gravity is necessary, due to low cost, ease of construction, and adequate compatibility with the substrate concrete. Silica-fume concrete or polymer-cement concrete is frequently substituted for concrete due to their increased bond strengths. As vertical and overhead repairs are more labor-intensive and frequently have smaller repair quantities, the cost premium for polymer-cement concrete is often not a controlling factor. Because form-and-cast repairs are self-curing while the forms remain in place, plastic shrinkage cracking and hardened cracking are normally reduced. Polymer concrete is used only in special situations where its good bond strength and durability characteristics offset its cost and special construction training requirements. It also requires special forming because of its strong adhesion to a wide range of materials.

3.1.3.2.2 *Preplaced-aggregate concrete repairs*—In the preplaced-aggregate concrete procedure, the coarse aggregate is preplaced in the form, and a cement-sand grout (usually with admixtures) or a resinous material is then injected into the form from the lowest point, resulting in a concrete or a polymer concrete repair. Preplaced-aggregate concrete contains a higher percentage of coarse aggregate than concrete that is formed and cast (ACI 304R and 304.1R).

Because the coarse aggregate is preplaced 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-aggre-

Table 3.1—Repair material selection guide for concrete replacements and overlays*

	Favorable properties	Unfavorable properties	Remarks
1. Deep concrete replacements and overlays			
A. Top surface applications			
Concrete	2, 3, 7, 8	1, 9, 10, 11	Most commonly used
Low-*w*/*cm* concrete	2, 3, 7, 8	1, 11	Improved durability
Silica-fume concrete	2, 3, 4, 5, 8, 9, 10, 11	1, 7	Significantly improved durability
Polymer-cement concrete	2, 3, 4, 5, 8, 9, 10, 11	1, 7	Significantly improved durability
Polymer concrete	1, 2,† 4, 5, 8, 9, 10, 11	1, 2,†3, 7, 12	Significantly improved durability; used in special situations
MAPCC	1, 2, 3, 4, 5, 6, 9, 10	11	Good durability, good dimensional stability, rapid setting. Used where quick application is desired. Not commonly used for overlays.
B. Vertical and overhead applications			
Concrete	2, 3, 8	1, 4, 5	Form-and-cast, preplaced aggregate, and shotcrete applications
Silica-fume concrete	2, 3, 4, 5, 6, 8, 9, 10, 11	1, 7	Form-and-cast and shotcrete applications
Polymer-cement concrete	2, 3, 4, 5, 6, 8, 9, 10, 11	1	Form-and-cast and shotcrete applications
Polymer concrete	4, 5, 6, 8, 9, 10, 11	1, 3, 7, 12	Form-and-cast and preplaced aggregate applications
Cement mortar	2,3	1	Shotcrete and occasionally trowel-applied applications
Silica-fume mortar	2, 3, 4, 5, 6, 9, 10, 11	1, 7	Shotcrete and occasionally trowel-applied applications
Polymer-cement mortar	2, 3, 4, 5, 6, 7, 9, 10, 11	1	Trowel-applied applications and shotcrete
Polymer mortar	4, 5, 6, 8, 9, 10, 11	1, 3, 12	Trowel-applied applications
2. Shallow concrete replacements and overlays			
Cement mortar	2	1, 3, 8	Poor durability; used in relatively benign applications
Silica-fume mortar	2, 4, 5, 6, 8, 9, 10, 11	1, 3	Improved durability; commonly used
Polymer-cement mortar	2, 4, 5, 6, 8, 9, 10, 11	1, 3	Improved durability; commonly used
Polymer mortar	4, 5, 6, 8, 9, 10, 11	1, 2, 3, 12	Good durability; used in special situations or as the application gets thinner
MAPCM	1, 2, 3, 4, 5, 6, 9, 10	11	Good durability, good dimensional stability, rapid setting.
3. Thin overlays			
Cement mortar	—	1, 3, 8	Sometimes used
Silica-fume mortar	4, 6, 8, 9, 11	1, 3	Good durability
Polymer-cement mortar	4, 6, 8, 9, 11	1, 3	Good durability
Polymer mortar	4, 5, 6, 8, 9, 11	1, 2, 3, 12	Good durability

*See important material properties key to favorable and unfavorable properties.
†For polymer concrete, a lower modulus of elasticity than the substrate concrete is beneficial in relieving differential stresses between the repair material and the substrate concrete, but is undesirable for structural repairs.

Important material properties
1—Volume stability

Mechanical properties:
2—Modulus of elasticity
3—Coefficient of thermal expansion
4—Bond strength
5—Tensile strength

Construction characteristics:
6—Cohesiveness
7—Ease of construction

External and chemical environment factors:
8—Freezing-and-thawing durability
9—Permeability
10—Electrical resistivity
11—Resistance to chemical attack
12—Low heat deflection or glass transition temperature

gate concrete is less than 1/2 that of conventional concrete because of the point-to-point contact of the coarse aggregate. The cement-sand grout may have a relatively high water content to yield a pumpable grout. This high water content can have an adverse effect on some of the cured material properties, such as permeability and porosity. Preplaced-aggregate polymer concrete has a coefficient of thermal expansion similar to portland-cement 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-compacted coarse aggregate, and to properly inject the grout or resin. Special equipment is 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 and silica fume, made specifically for preplaced aggregate repairs (Watson 1996), and applications with polymer-cement grout have proven successful.

3.1.3.2.3 *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 mortar, and polymer-cement concrete and mortar (Table 3.1) can all be placed by shotcreting. All of 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 ASTM C 1436, and prepackaged shotcrete should comply with ASTM C 1480. 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 13 mm (1/2 in). Fiber reinforcement or welded-wire reinforcement can be used to help control the cracking. Refer to ACI 506.1R for further information.

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.

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 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. Experience has shown that early and thorough wet curing of silica fume shotcrete is highly desirable to prevent formation of excessive cracks during the curing process. Because of the difficulty in mixing, handling, and cleaning, polymer-cement concrete and mortar are not commonly used for shotcrete.

3.1.3.2.4 *Trowel-applied repairs*—In 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. 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 the coarse aggregate decreases the cohesiveness to the point where the material is weaker than the pull of gravity and falls out of the repair area before the material can set.

Repair materials include cement mortar, silica-fume mortar, polymer-cement mortar, and polymer mortar. Trowel-applied repairs are used for deep concrete replacements only in unusual circumstances, such as when the concrete replacements are limited in size 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.

3.1.4 *Shallow concrete replacements and overlays*—Repair materials for shallow concrete replacements and overlays, defined for the purposes of this guide as at least 1.6 to 3.2 mm (1/16 to 1/8 in.) thick and less than 19 to 25 mm (3/4 to 1 in.), include fine aggregates only. Concrete replacements and overlays that are at least 19 mm (3/4 in.) in thickness commonly contain some coarse aggregate. Shallow concrete replacements and overlays are differentiated from deep concrete replacements and overlays in that repair mortars are generally used in shallow repairs. The materials most commonly used are cement mortar, silica-fume mortar, polymer-cement mortar, MAPCM, and polymer mortar (Table 3.1).

The properties of repair mortars are less compatible with the properties of the substrate concrete compared with the concrete mixtures used in deep repairs. Increased shrinkage and cracking are common problems for shallow concrete replacement and overlay materials, which may necessitate further repairs. Polymer repair mortars have coefficients of thermal expansion sufficiently different from the substrate concrete so that relative movements can occur between the repair mortar and the 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 becomes more important for achieving a satisfactory application. Timely and adequate curing is critical, except for polymer mortar that does not require curing. Where possible, the addition of even small-sized coarse aggregate (6 to 10 mm [1/4 to 3/8 in.]) can be beneficial to the performance of the repair.

Cement mortar is sometimes used for shallow concrete replacements and overlays, but it is susceptible to cracking due to the restraint of shrinkage and higher drying shrinkage. Silica-fume mortar and polymer-cement mortar are commonly used because their increased bond and tensile strengths help to offset the effects of anticipated shrinkage. Their excellent bond and cohesiveness before setting also allow these materials to be placed in thicker lifts for overhead and vertical applications, increasing productivity. Polymer mortar is sometimes used, although special attention should be given to the mixture proportion and the repair details. Thermal incompatibility between polymer mortar and the substrate concrete seldom causes cracking and debonding of concrete replacements, even in situations where service temperature may vary widely. In addition, the excellent bond and tensile strengths and durability characteristics make it a good repair option in most thin repair situations (refer to ACI 548.1R).

3.1.5 *Thin overlays*—Thin overlays, defined for the purposes of this guide as those less than 1.6 to 3.2 mm (1/16 to 1/8 in.) 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-cement mortar, and polymer mortar (Table 3.1). 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 becomes critical for satisfactory repair performance, and construction workers frequently require special training in the mixing and placement of the repair material. Timely and adequate curing is critical.

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 the differential behavior with the substrate concrete. Silica-fume mortar, polymer-cement mortar, and polymer mortar are commonly used because of their increased bond and tensile strengths and improved durability characteristics. The dimension 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, and the excellent bond and tensile strengths of polymer mortar often offset the generated stresses.

3.1.6 *Aggressive environments and exterior applications*—In aggressive environments and exterior applications, the repair approach may include coatings for reinforcing bars exposed in concrete replacement areas, or surface sealers or coatings on the replacements or on the entire member or structure, to improve the overall durability of the structure. 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 replacements 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, polymer-cement concrete, or polymer concrete is sometimes used. Refer to ACI 201.2R for a discussion of various ways to improve concrete durability.

3.2—Crack repair

3.2.1 *General*—Cracks are objectionable in concrete for several reasons. Aesthetically, they may be considered unsightly. Cracks may allow for the accelerated degradation of the concrete, corrosion of the reinforcing steel, or both, by allowing easy access by moisture, oxygen, chlorides, carbon dioxide, and other aggressive chemicals and gases into the concrete. While the crack itself may or may not be a problem, it is often the symptom of a condition that may very well be a problem. If left untreated, cracks may eventually lead to the serious degradation of the structure or failure of structural components. The goal of all crack repairs is to achieve one or more of the following objectives (ACI 224.1R):

1. Restore and increase the strength of cracked components;
2. Restore and increase the stiffness of cracked components;
3. Improve functional performance;
4. Prevent liquid penetration;
5. Improve the appearance of the concrete surface;
6. Improve durability; and
7. Prevent development of a corrosive environment at the reinforcement.

Additionally, repair of cracks may:

- Improve hygiene by improving cleanability;
- Reduce gas permeability; and
- Reduce sound transmission.

For repair evaluation, cracks are categorized based on causes, width, stability (whether the crack is active or dormant), environmental conditions to which the crack is exposed (if it is wet, actively leaking, or exposed to deleterious chemicals), and structural requirements. Only a qualified design professional should determine if a crack is a significant structural problem that should be repaired. Structural cracks are caused by dead loads, applied loads and forces, and other external influences (Concrete Society 1985). Once the design professional has determined the requirements of the repair, selection of the crack repair material can be made. Refer to ACI 224.1R and U.S. Army Corps of Engineers (USACE) EM 1110-2-2002 for further information regarding the causes, evaluation, and repair of cracks, and to Table 2.2 for a summary of available test methods for crack repair materials.

There are numerous crack repair materials available to the specifier. Additional information about each material, such as advantages, limitations, specific applications, and standards, serve to help the specifier determine which of the available materials represents the best choice for a specific repair. This information is summarized in the remainder of this section.

3.2.2 *Crack widths less than 0.05 mm (0.002 in.)*—Cracks less than 0.05 mm (0.002 in.) in width are generally not treated or considered treatable. Very thin cracks may seal themselves due to autogeneous healing, which occurs when the cement continues to hydrate and carbonates, forming calcium carbonate and calcium hydroxide crystals that can seal the crack. Minimally, the structure should be inspected periodically to monitor any potential increase in the crack widths over time. Increasing crack widths over time are indicative of other problems that should be assessed and evaluated to determine what repairs, if any, are needed.

3.2.3 *Crack widths greater than 0.05 mm (0.002 in.)*

3.2.3.1 *Epoxy resin*—Epoxies are a generic group of synthetic resins. Epoxy resins always require thorough mixing with a hardener or curing compound, usually an amine or a polyamide, to initiate the chemical reaction that results in their exceptional adhesive properties.

Because of their high adhesive strength, epoxies are widely used for structural bonding and waterproofing repairs. Some epoxies are moisture-tolerant and will cure in the presence of moisture. While a few epoxies may effectively bond to concrete with some moisture present in the concrete pores, most epoxies marketed to the engineering and construction community will not bond to the concrete in the presence of moisture. Available in a wide range of viscosities, moduli, and reaction rates, epoxies may be formulated to accommodate the needs of nearly every application requirement. Epoxies undergo negligible shrinkage, which is important if the repair is to perform as specified.

The resin and hardener should be accurately proportioned and well mixed. Any deviation can result in a material that remains soft or tacky and fails to comply with the specified requirements. As a result, experienced application personnel are essential, and special injection equipment is required. If the cracks have dirt or other contaminants on their internal surfaces, the epoxy may not bond adequately to the surfaces, reducing the effectiveness of the repair. Most epoxies have very limited flexibility, and can tolerate very slight movement at the crack. If there is a tendency for widening of a crack, the concrete is likely to crack adjacent to the repaired crack.

Ambient-temperature-cured epoxies conforming to the requirements of ASTM C 881/C 881M Type IV that are used for crack repairs with widths greater than 0.05 mm (0.002 in.) have a heat deflection temperature of at least 50 °C (120 °F). If the repair is intended to restore or increase the strength or stiffness of the member, the repair should be evaluated to ensure that a fire would not threaten the safety of the member. The temperature exposure of the material within a crack, however, is usually less than at the surface, and high surface temperature exposure does not necessarily mean a loss of structural integrity of the material within the crack due to the insulating properties of the surrounding concrete.

As with most any repair, the best results will always be achieved by the most qualified and skilled application personnel. A high level of skill is required for injection, as often times the repairs are structural in nature.

Epoxies are used to repair cracks ranging from 0.05 to 6 mm (0.002 to 0.250 in.) in width. The most common method of application in the range of 0.05 to 0.12 mm (0.002 and 0.005 in.) is pressure injecting material into the crack. Epoxy resins are the most common materials used in pressure injection to repair cracks in this width range. Specific details with respect to application techniques are beyond the scope of this guide. Details on application techniques are provided in ACI 224.1R and ACI 503R. Cracks in horizontal slabs that are between 0.10 and 6 mm (0.004 and 0.250 in.) may be filled by gravity or ponding the epoxy over the crack. The depth of penetration is determined by the viscosity, pot life, and surface tension of the epoxy resin. On-site testing, such as core examination and bleed-through verification, should be conducted to confirm adequate penetration and performance. Vertical and overhead applications and thinner horizontal applications are generally pressure injected. Epoxies may be extended with sand to make a grout for repairing larger cracks.

ASTM C 881/C 881M classifies epoxies by their intended use, viscosity, and temperature limitations. The standard classifies epoxies into seven different types of epoxies. Injection resins are normally classified as Type I, non-load-bearing applications for bonding hardened concrete to hardened concrete, or Type IV, load-bearing applications for bonding hardened concrete to hardened concrete.

3.2.3.2 *High-molecular-weight methacrylate (HMWM)*—HMWM is an ester of methacrylic acid that contains carbon atoms separated by double bonds through which the material polymerizes to a solid. High molecular weight is a term used to differentiate methacrylates by high and low volatile content and flash point; this molecular weight has been arbitrarily chosen as 150.

High adhesive strengths make these materials suitable for structural repairs. Low viscosities (25 cP and less) and a more forgiving mixing ratio than epoxies make these materials easy to mix. HMWMs are available in many moduli and reaction rates, making them versatile materials appropriate for many application requirements.

HMWMs are sensitive to moisture; therefore, the substrate should be dry at the time of application to obtain the required bond. Ambient-temperature-cured HMWMs used for this type of application may show a detectable loss of strength at elevated temperatures. This characteristic does not normally affect the repair performance under atmospheric conditions, but could become a factor for repair environments that exceed atmospheric conditions.

Three-component systems are available; however, they are potentially explosive if the components are not mixed in the proper order. Two-component products are much safer, as they eliminate the importance of the order in which the components are combined.

HMWMs are typically used as a structural bonding, waterproofing repair, or both, for cracks 0.12 mm (0.005 in.) and greater in width. Because of their low viscosities, HMWMs are often used on horizontal surfaces to flood the surface and fill the cracks with the adhesive. This method of repair is also known as gravity filling, and requires materials with low viscosities (less than 25 cP) to fill the crack using gravity as the only force. HMWM may also be pressure injected; however, this is rare because the typical viscosity of pressure injection materials is between 100 and 500 cP (ACI 503.5R). There is no standard specification for HMWMs similar to that for epoxies; however, ASTM is currently developing a standard (ASTM WK 2165). As in the case of epoxy resins, ASTM C 882 can be used for evaluating the bonding of HMWMs. This test method is described in Chapter 2.

3.2.3.3 *Polyurethane chemical grout*—Although there are other forms of chemical grouts, polyurethanes are by far the most common choice of material for repair of cracks by chemical grouting, and are classified into hydrophobic and hydrophilic types. Polyurethane chemical grouts consist of a polyurethane resin that reacts with water to form an expansive, closed-cell foam (hydrophobic types) or gel (hydrophilic types). Hydrophobic types are generally recommended for applications subject to intermittent wetting and drying; hydrophilic types should be continuously wet (USACE EM 1110-1-3500).

Polyurethane chemical grouts are usually used to repair cracks that are both wet and active, or that are leaking a significant amount of water. These grouts are semiflexible; thus, they may tolerate some change in crack width. The reaction time to form the foam may be controlled from a few seconds up to several minutes using different catalyst additives. For example, where a crack is leaking heavily, the polyurethane chemical grout reaction may be highly accelerated to stop the leak. These grouts penetrate effectively, and the technique of chemical grouting is a well-proven method of repairing cracks.

Polyurethane chemical grouts generally are not suitable for structural repairs. Additionally, a highly skilled work crew is required along with special injection equipment. Finally, these materials typically are not stable when exposed to UV light. This is usually not a major concern because the material is injected into a narrow crack where exposure to UV light is minimal.

Polyurethane chemical grouts may be used to treat cracks that are 0.12 mm (0.005 in.) and greater in width. These materials are pressure injected at high pressures. In contrast to epoxy resins that are suitable for dormant, dry or damp cracks, polyurethane chemical grouts are suitable for injection of vertical, overhead, and horizontal cracks that are active or leaking. These characteristics make them particularly suited for vertical, overhead, and horizontal applications, and it is their ability to stop active leaks that makes them particularly well suited for tanks for the storage of liquids, dams, tunnels, sewers, and other water-containment structures.

No standards currently exist for polyurethane chemical grouts. ASTM D 1623 may be used to determine the tensile strength and elongation properties of the grout at all urethane-to-water ratios.

3.2.3.4 *Polyurethane sealant*—Polyurethane products result from a reaction between an isocyanate group and a hydroxyl group. Typical polyurethane sealants will contain a polymer, fillers, colorants, curing agents, adhesion additives, thixotropic agents, plasticizers, and solvent (Panek and Cook 1992). Refer to ACI 504R for further information.

Polyurethane sealants generally provide an excellent bond to clean concrete and masonry surfaces, and usually do not require a primer to obtain this excellent adhesion. The use of a primer, however, is beneficial in many applications where increased adhesion is needed or in situations where the bonding surfaces are not as well prepared as is desirable. Polyurethane sealants can provide a service life from 3 to 10 years; one reason is their ability to relieve the stress at the bond line, caused by constant elongation of the joint, through controlled internal flow. Very high elongation properties make these materials suitable for active joints. Polyurethane sealants have excellent weathering resistance properties; thus, they will maintain their original material properties over time. Certain formulations of these materials may be placed in submerged environments, such as joints within water tanks and reservoirs, because their physical properties will be unaffected, even under constant immersion. Although on-site mockups should be constructed to verify compatibility with different materials, polyurethane sealants are generally compatible with concrete and masonry; consequently, they will not react with or stain the substrate. These materials do not require a high level of skill to apply. Coatings may be applied to some polyurethane sealants for a more uniform appearance, particularly in wall panels of a building. Sealants are not suitable for structural repairs. While the chemical resistance is generally not as good as an epoxy, some sealants with enhanced resistance are available; sealant manufacturers should be consulted regarding the suitability of specific sealants for specific exposures. Although the performance of the material is not unusually affected by UV light, the surface will tend to form a white, dusty deposit on the sealant surface (known as chalking) under long-term exposure. For optimum performance, polyurethane sealants should have regular inspections and maintenance.

Polyurethane sealants are generally used to seal cracks that are from 2.5 to 50 mm (0.1 to 2 in.) in width. Proper design of the joint and sealant profile is critical to ensure the sealant performs as specified. A single direction of joint movement is usually required for good sealant performance, and bond breakers within the joint are frequently used to allow the sealant to contract vertically when stretched horizontally (just as a rubber band gets thinner when stretched). Stress buildup in the sealant is minimized as the width-depth ratio approaches 2:1. The maximum joint width is generally 25 mm (1 in.); however, some products may be applied up to 50 mm (2 in.) in width. The minimum joint width is 6 mm (1/4 in.); therefore, smaller cracks have to be routed to comply with this limitation. The minimum joint depth is generally about 6 mm (1/4 in.), and the maximum depth is about 13 mm (1/2 in.). These sealants are available in single and two components. Single-component products are ready to use and do not require mixing; however, the color selection may be limited, and sufficient humidity must be present for proper curing. Two-component products should be thoroughly mixed before using; they may cure faster in cold environments, and there is greater diversity in color choices.

Polyurethane sealants come in a variety of consistencies and hardnesses, making them suitable for vertical and overhead applications. Polyurethane sealants are also appropriate for horizontal applications exposed to vehicular traffic as long as the Shore A hardness is between 25 and 50 when tested in accordance with ASTM C 661 (ASTM C 920).

ASTM C 920 covers properties of a cured single- or multi-component elastomeric joint sealant used for sealing, caulking, or glazing operations on buildings, plazas, and decks for vehicular or pedestrian use. Federal Specification TT-S-00230C is for single-component sealants used for caulking, sealing, and glazing. ASTM C 920 has superseded Federal Specification TT-S-00227E and CID A-A-1556A, but both of these superseded specifications continue to be referenced.

3.2.3.5 *Silicone sealant*—Silicone sealants are based on polymers where the polymer backbone consists of alternating silicon and oxygen atoms with carbon-containing side groups. They have different curing mechanisms, depending on the end group of the polymer (ASM International 1990). Typically, silicone sealants contain silicone polymers, fumed silica, plasticizers, calcium carbonate fillers, and silanes for adhesion (Panek and Cook 1992). Sealant performance life typically is 3 to 10 years.

Silicone sealants are highly resistant to UV light, and do not chalk or change color even when exposed for long periods of time. Silicone sealants have high elongation properties (1000% and greater), making them suitable for active joints. Silicone sealants are not suitable for structural repairs. The adhesion to concrete and masonry is suspect unless a primer is used. Silicone sealants are not recommended for immersion; thus, they are not used for sealing joints within water tanks, reservoirs, dams, and the like. Silicone

sealants behave poorly with respect to stress relaxation. When the joint widens, greater stress builds up, particularly at the bond line, which may result in adhesion loss or tearing of the sealant. These materials may only be over-coated with silicone-based coatings. Finally, oils within the silicone will often migrate into a porous substrate. The result may be staining of the substrate, making these materials aesthetically unacceptable. Long-term testing data should always be reviewed before specifying these materials. For optimum performance, silicone sealants should have regular inspections and maintenance.

Silicone sealants are generally used to seal cracks that are from 2.5 to 50 mm (0.1 to 2 in.) in width. As in the case of polyurethanes, joint design is critical to ensure that the sealant material behaves properly. Three-dimensional adhesion should be prevented. A 2:1 joint width-depth ratio should be maintained. Joint widths should range from 6 to 25 mm (1/4 to 1 in.), and depths should range from 6 to 13 mm (1/4 to 1/2 in.). Therefore, smaller cracks will have to be routed to comply with this limitation. Silicone sealants are suitable for vertical and overhead applications. Some manufacturers offer sealant formulations that are suitable for traffic. When applied horizontally, they should be recessed and protected from traffic loads. Most silicone sealants are packaged as a single component; however, they are also available in two-component systems.

ASTM C 920 and Federal Specifications TT-00230C and TT-001543A can be used for silicone sealants

3.2.3.6 *Polymer grout*—Polymer grout is a mixture where the polymer, such as an epoxy resin, serves as the binder, and where sand, usually an oven-dried silica with a grading from 0.8 to 0.4 mm (No. 20 to +40 mesh) is the filler. The consistency of this material may vary from a stiff material suitable for hand-packing large cracks on overhead and vertical surfaces to a pourable consistency suitable for gravity feeding cracks in horizontal slabs.

Polymer grouts bond extremely well to concrete and have low shrinkage, resulting in a liquid-tight repair in dormant cracks. Similar to epoxy resins, polymer grouts are suitable for cracks requiring structural repairs. Materials of varying consistencies are readily available to repair cracks in vertical, overhead, and horizontal applications. Some polymer grouts, depending on the binder used, are moisture-tolerant, and will cure in the presence of moisture. While a few polymer grouts may effectively bond to concrete with some moisture present in the concrete pores, most polymer grouts marketed to the engineering and construction community will not bond to the concrete in the presence of moisture. The chemical resistance of polymer grout is generally much better than the substrate concrete. Finally, these materials may be designed for a fast cure to minimize the downtime because of repairs.

As with epoxy resins, it is critical to properly proportion and thoroughly mix polymer grouts. Failure to do so could result in a repair that never cures or cures sporadically. Generally, the temperature exposure of these materials should not exceed 82 to 93 °C (180 to 200 °F). It is at these temperatures that the first detectable loss of strength may occur.

Polymer grout is typically used to repair dormant cracks that are 6 mm (0.25 in.) and greater in width. Polymer grouts can be hand-applied and packed into large cracks, regardless of orientation, or they can be poured into cracks located within horizontal slabs. No special equipment is required to apply these materials, and the required applicator skill levels are low to moderate. The resin and hardener are mixed, and then the filler is gradually added while mixing until a homogenous mixture is achieved. Mixing is typically done with an eggbeater-style mixing blade and a hand-held electric drill. Pot life or working time may be varied to suit the application. Long pot life products enable the applicator to mix and apply larger quantities. Fast-cure products allow rapid turnovers; however, care should be taken to mix only sufficient material that may be applied within the specified pot life.

No standards currently exist for polymer grouts intended for use as crack repair. ASTM C 882, D 638, and D 695 are among the recommended tests to consider when evaluating these materials.

3.2.3.7 *Polymer-cement grout*—Polymer-cement grout is a mixture consisting primarily of cement, fine aggregate, water, and a polymer such as acrylic, styrene-acrylic, styrene-butadiene, or a water-borne epoxy. The consistency of this material may vary from a stiff material suitable for hand-packing large cracks on overhead and vertical surfaces to a pourable consistency suitable for gravity feeding cracks in horizontal slabs.

These materials are available in a wide range of consistencies suitable for many applications. No special tools and equipment are necessary, and the required applicator skill levels are low to moderate. These materials are generally more economical than polymer grouts, and the performance, with respect to bond strength, tensile strength, and flexural strength, are improved compared with cement-based materials that do not contain any polymers.

The potentially high shrinkage of polymer-cement grouts compared with polymer grouts may make it difficult to obtain a watertight repair. Additionally, these materials are not as chemically resistant as the polymer grouts.

Polymer-cement grout is generally used to repair cracks that are 6 mm (0.25 in.) and greater in width. The surface should be prepared to ensure a clean, open-pore substrate. The substrate should be in a saturated-surface-dry (SSD) condition, with no standing water at the time of application. Mixing may be done using a drill and paddle or a mixer. The material should be scrubbed into the substrate to fill all pores and voids, and then packed into the crack and finished flush with the concrete surface. The polymer component should conform to the requirements of ASTM C 1438, Type II. No standards exist for mixtures of the polymer component with grout; however, recommended tests for these materials are found in ASTM C 1439 as well as ASTM C 157/C 157M, C 293, C 469, C 496/C 496M, and C 531.

3.2.3.8 *Cementitious grout*—A grout is a mixture of cementitious material and water, with or without aggregate, that is proportioned to produce a pourable consistency without segregation of constituents (ACI 116R).

Cement-based grouts are available in a wide range of consistencies; therefore, the methods of application are diverse. These materials are perhaps the most economical of the choices contained in this guide. They do not require unusual skill or special equipment to apply, and are reasonably safe to handle. These materials tend to have similar properties to the parent concrete, and have the ability to undergo autogeneous healing due to subsequent hydration of cementitious materials at fracture surfaces. Cement-based grouts are not suitable for structural repairs of active cracks.

Cementitious grout may be used to repair cracks that are 6 mm (0.25 in.) and greater in width. Generally, some form of routing and surface preparation, such as removal of loose debris and prewetting to achieve a SSD condition, are required to obtain the minimum required width and suitable substrate appropriate for the use of these materials.

One of the most common uses of cement-based grouts in crack repair is to simply provide a fill for the crack before the application of a coating. While grouts are generally mixed to a pourable consistency, as stated previously, the consistency may be adjusted for application by hand troweling or dry packing into vertical and overhead cracks.

There are no standards developed strictly for grouts used for crack repair. ASTM C 1107 is intended for materials used under applied loads such as base plates for a structure or machine.

3.2.3.9 *Strip-and-seal system*—Strip-and-seal systems consist of a flexible sheet, such as synthetic rubber, that spans over a crack and is adhered to the structure on each side of the crack using a suitable adhesive. These systems are designed to span over the crack and prevent leakage of liquids; the crack itself is not actually filled or repaired.

Some systems have a high resistance to aggressive chemicals. These systems have virtually no limitation to the crack width. Moisture-insensitive epoxies may be used as an adhesive on damp surfaces. The elongation properties of these systems are excellent, making them appropriate for use on active joints. Some strip-and-seal systems are highly resistant to UV light; thus, they do not chalk or weather. Generally, these systems do not require any special worker skills or equipment to install.

Strip-and-seal systems are not suitable for structural repair. Strip-and-seal systems are designed to be applied to the positive-pressure side of a structure, thus preventing leakage of liquid into or out of the structure.

Strip-and-seal systems may be used to treat cracks of any width, but are most commonly used to treat cracks that are 6 mm (0.25 in.) or greater in width. Strip-and-seal systems are particularly suited for stopping leaks that may otherwise be difficult to seal with other materials. These systems may be applied vertically, horizontally, or overhead.

ASTM D 412 may be used to determine the tensile strength and elongation percent of the sheeting at failure. ASTM D 903 may be used to determine the adhesive strength of the sheeting to the adhesive and the adhesive to the concrete.

CHAPTER 4—REFERENCES

4.1—Referenced standards and reports

The standards and reports listed below were current at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute (ACI)

116R	Cement and Concrete Terminology
201.2R	Guide to Durable Concrete
211.1	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
221.1R	Report on Alkali-Aggregate Reactivity
222R	Protection of Metals in Concrete Against Corrosion
224.1R	Causes, Evaluation, and Repair of Cracks in Concrete Structures
234R	Guide for the Use of Silica Fume in Concrete
304R	Guide for Measuring, Mixing, Transporting, and Placing Concrete
304.1R	Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications
304.2R	Placing Concrete by Pumping Methods
304.5R	Batching, Mixing, and Job Control of Lightweight Concrete
304.6R	Guide for the Use of Volumetric-Measuring and Continuous-Mixing Concrete Equipment
308R	Guide to Curing Concrete
503R	Use of Epoxy Compounds with Concrete
503.5R	Guide for the Selection of Polymer Adhesives with Concrete
504R	Guide to Sealing Joints in Concrete Structures
506R	Guide to Shotcrete
506.1R	Committee Report on Fiber Reinforced Shotcrete
515.1R	Guide to the Use of Waterproofing, Dampproofing, Protective, and Decorative Barrier Systems for Concrete
546R	Concrete Repair Guide
548.1R	Guide for the Use of Polymers in Concrete
548.3R	Polymer-Modified Concrete
548.5R	Guide for Polymer Concrete Overlays

ASTM International

C 39/ C 39M	Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 78	Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C 109/ C 109M	Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
C 157/ C 157M	Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
C 190	(discontinued in 1991) Method of Test for Tensile Strength of Hydraulic Cement Mortars (Withdrawn 1990)

C 227	Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
C 273	Test Method for Shear Properties of Sandwich Core Materials
C 289	Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)
C 293	Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)
C 295	Guide for Petrographic Examination of Aggregates for Concrete
C 307	Test Method for Tensile Strength of Chemical-Resistant Mortar, Grouts, and Monolithic Surfacings
C 348	Test Method for Flexural Strength of Hydraulic-Cement Mortars
C 418	Test Method for Abrasion Resistance of Concrete by Sandblasting
C 469	Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
C 496/ C 496M	Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
C 510	Test Method for Staining and Color Change of Single- or Multicomponent Joint Sealants
C 512	Test Method for Creep of Concrete in Compression
C 531	Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes
C 580	Test Method for Flexural Strength and Modulus of Elasticity of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes
C 596	Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement
C 642	Test Method for Density, Absorption, and Voids in Hardened Concrete
C 661	Test Method for Indentation Hardness of Elastomeric-Type Sealants by Means of a Durometer
C 666/ C 666M	Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 672/ C 672M	Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
C 679	Test Method for Tack-Free Time of Elastomeric Sealants
C 719	Test Method for Adhesion and Cohesion of Elastomeric Sealants Under Cyclic Movement (Hockman Cycle)
C 779/ C 779M	Test Method for Abrasion Resistance of Horizontal Concrete Surfaces
C 794	Test Method for Adhesion-in-Peel of Elastomeric Joint Sealants
C 806	Test Method for Restrained Expansion of Expansive Cement Mortar
C 827	Test Method for Change in Height at Early Ages of Cylindrical Specimens of Cementitious Mixtures
C 881/ C 881M	Specification for Epoxy-Resin Base Bonding Systems for Concrete
C 882	Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete By Slant Shear
C 884/ C 884M	Test Method for Thermal Compatibility Between Concrete and an Epoxy-Resin Overlay
C 920	Specification for Elastomeric Joint Sealants
C 944	Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method
C 1012	Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
C 1042	Test Method for Bond Strength of Latex Systems Used with Concrete By Slant Shear
C 1107	Specification for Packaged Dry, Hydraulic-Cement Grout (Nonshrink)
C 1138	Test Method for Abrasion Resistance of Concrete (Underwater Method)
C 1181	Test Methods for Compressive Creep of Chemical-Resistant Polymer Machinery Grouts
C 1202	Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
C 1260	Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
C 1293	Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction
C 1404/ C 1404M	Test Method for Bond Strength of Adhesive Systems Used with Concrete as Measured by Direct Tension
C 1436	Specification for Materials for Shotcrete
C 1438	Specification for Latex and Powder Polymer Modifiers for Hydraulic Cement Concrete and Mortar
C 1439	Test Methods for Polymer-Modified Mortar and Concrete
C 1480	Specification for Packaged, Pre-Blended, Dry, Combined Materials for Use in Wet or Dry Shotcrete Application
C 1581	Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete Under Restrained Shrinkage
C 1583	Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)
D 412	Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension
D 570	Test Method for Water Absorption of Plastics
D 624	Test Method for Tear Strength of Conventional Vulcanized Rubber and Thermoplastic Elastomers
D 638	Test Method for Tensile Properties of Plastics
D 648	Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position
D 695	Test Method for Compressive Properties of Rigid Plastics

D 696 Test Method for Coefficient of Linear Thermal Expansion of Plastics Between –30 °C and 30 °C with a Vitreous Silica Dilatometer
D 732 Test Method for Shear Strength of Plastics by Punch Tool
D 790 Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
D 903 Test Method for Peel or Stripping Strength of Adhesive Bonds
D 1623 Test Method for Tensile and Tensile Adhesion Properties of Rigid Cellular Plastics
D 2126 Test Method for Response of Rigid Cellular Plastics to Thermal and Humid Aging
D 2393 Test Method for Viscosity of Epoxy Resins and Related Components (withdrawn)
D 2566 Test Method for Linear Shrinkage of Cured Thermosetting Casting Resins During Cure (withdrawn)
WK 2165 Specification for High Molecular Weight Methacrylate (HMWM) Monomer Systems for Sealing and Patching Concrete

American Association of State and Highway Transportation Officials (AASHTO)
T 259 Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration
T277 Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete
PP 34 Practice for Estimating the Cracking Tendency of Concrete

Canadian Standards Association
CSA A23.2-6B Method of Test to Determine Adhesion by Tensile Load
CSA A864-00 Guide to the Evaluation and Management of Concrete Structures Affected by Alkali-Aggregate Reaction

United States Army Corps of Engineers
CRD-C 39 Coefficient of Linear Thermal Expansion of Concrete
CRD-C 164 Standard Test Method for Direct Tensile Strength of Cylindrical Concrete or Mortar Specimens
EM 1110-1-3500 Chemical Grouting
EM 1110-2-2002 Evaluation and Repair of Concrete Structures

Federal specifications
CID A-A-1556A Sealing Compound (Elastomeric Joint Sealant)
TT-S-00227E Sealing Compound: Elastomeric Type, Multi-Component (For Caulking, Sealing, and Glazing in Buildings and Other Structures)
TT-S-00230C Sealing Compound: Elastomeric Type, Single Component (For Caulking, Sealing, and Glazing in Buildings and Other Structures)
TT-S-001543A Sealing Compound: Silicone Rubber Base (For Caulking, Sealing, and Glazing in Buildings and Other Structures)

These above publications may be obtained from the following organizations:

American Concrete Institute (ACI)
P.O. Box 9094
Farmington Hills, MI 48333-9094
www.concrete.org

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

American Association for State Highway Transportation Officials
444 North Capitol Street NW, Suite 249
Washington, DC 20001-1539
http://www.aashto.org

Canadian Standards Association
5060 Spectrum Way, Suite 100
Mississauga, Ontario
L4W 5N6 CANADA
www.csa.ca

United States Army Corps of Engineers
USACE Publication Depot
ATTN: CEIM-IM-PD
2803 52nd Ave.
Hyattsville, MD 20781-1102
http://www.wes.army.mil/SL/MTC/handbook/handbook.htm

4.2—Cited references

Ashby, M. F., 1992, *Materials Selection in Mechanical Design*, Pergamon Press, London, 311 pp.

ASM International, 1990, *Engineered Materials Handbook,* V. 3: Adhesives and Sealants, Metals Park, Ohio, 893 pp.

Beaudoin, J. J., 1982, "Fibre-Reinforced Concrete," *Canadian Building Digest*, CBD-223, National Research Council Canada, Institute for Research in Construction.

Concrete Society, 1976, "Concretes with Dispersed Polymers Added," *Polymers in Concrete: Proceedings of the First International Congress on Polymer Concretes*, D. H. Cohen, ed., Concrete Construction Publications, Inc., Addison, Ill., pp. 179-240.

Concrete Society, 1985, "Non-Structural Cracks in Concrete: Report of a Concrete Society Working Party," *Technical Report* No. 22, London, 38 pp.

Gurjar, S., 1987, "Alberta Concrete Patch Evaluation Program," *Report* No. ABTR/RD/RR-87/05, Alberta Trans-

portation and Utilities, Research and Development, Edmonton, Alberta, Canada, 69 pp.

International Concrete Repair Institute (ICRI), 1996, "Guide for Selecting and Specifying Materials for Repair of Concrete" *Guideline* No. 03733, Des Plains, Ill., 34 pp.

International Concrete Repair Institute (ICRI), 2002, "Concrete Repair Terminology—Draft," Des Plains, Ill., 52 pp.

International Concrete Repair Institute (ICRI), 2003, "Guideline for Repair Material Data Sheet Protocol—Draft," Des Plains, Ill., Mar., 8 pp.

International Concrete Repair Institute (ICRI), 2004, "Guide to Using In-Situ Tensile Pull-off Tests to Evaluate Bond of Concrete Surface Materials," *Guideline* No. 03739, Des Plains, Ill., 10 pp.

Iriya, K.; Hattori, T.; and Umehara, H., 1999, "Study on the Relationship Between Compressive Creep and Tensile Creep of Concrete at an Early Age," *Civil Engineering*, No. 33, Japan Society of Civil Engineers, June.

Iriya, K.; Negi, T.; Hattori, T.; and Umehara, H., 2000, "Study on Tensile Creep of Concrete at an Early Age," *Civil Engineering*, No. 35, Japan Society of Civil Engineers, June.

Johnston, C., 1993, "Superplasticizers for Concrete Bridge Construction," *Report* No. ABTR/RD/RR-93/01, Alberta Transportation and Utilities, Research and Development, Edmonton, Alberta, Canada.

Knab, L. I.; Sprinkel, M. M.; and Lane, O. J., 1989, "Preliminary Performance Criteria for the Bond of Portland Cement and Latex Modified Concrete Overlays," *NISTR 89-4156*, National Institute of Standards and Technology, Gaithersburg, Md., 102 pp.

McDonald, J. E.; Vaysburd, A. M.; Emmons, P. H.; Poston, R. W.; and Kesner, K. E., 2002, "Selecting Durable Repair Materials: Performance Criteria—Summary," *Concrete International*, V. 24, No. 1, Jan., pp. 37-44.

Michigan Department of Transportation (MDOT), "Direct Shear Bonding Test-Qualification Procedure for Prepackaged Hydraulic Patching Mortars," 1 p.

Mindness, S., and Young, J. F., 1981, *Concrete*, Prentice-Hall, Englewood Cliffs, N.J., pp. 561, 624-628.

Neville, A. M., 1996, *Properties of Concrete*, 4th Edition, John Wiley, New York, 844 pp.

Panek, J. R., and Cook, J. P., 1992, *Construction Sealants and Adhesives*, 3rd Edition, John Wiley, New York, 375 pp.

Pigeon, M., and Bissonnette, B., 1999, "Tensile Creep and Cracking Potential," *Concrete International*, V. 21, No. 11, Nov., pp. 31-35.

Popovics, S., and Rajendran, N., 1987, "Early Age Properties of Magnesium Phosphate-Based Cements Under Various Temperature Conditions," *Concrete and Concrete Construction*, Transportation Research Record 1110, Washington, D.C., pp. 34-44.

Popovics, P.; S.; Rajendran, N.; and Penko, M., 1987, "Rapid Hardening Cements for Repair of Concrete," *ACI Materials Journal,* V. 84, No. 1, Jan.-Feb., pp. 64-73.

Portland Cement Association (PCA), 1996, "Thickness Design for Concrete Pavements," Skokie, Ill.

Portland Cement Association, 2001, "Effects of Substances on Concrete and Guide to Protective Treatments," PCA IS001, Skokie, Ill., 33 pp.

Shydlowski, L. M., 1998, "Challenges in the Commercialization of New Technologies," *Concrete International*, V. 20, No. 2, Feb., pp. 25-27.

Silfwerbrand, J., 1990, "Improving Concrete Bond in Repaired Bridge Decks," *Concrete International*, V.12, No. 9. Sept., pp. 61-66.

Sprinkel, M. M., and Ozyildirim, H. C., 1998, "Field Evaluation of Corrosion Inhibitors for Concrete: Interim Report 1, Evaluation of Exposure Slabs Repaired With Corrosion Inhibitors," *Report* No. VTRC 99-IR1, Virginia Transportation Research Council, Charlottesville, Va., 60 pp.

Stark, D., 1991, "The Moisture Condition of Field Concrete Exhibiting Alkali-Silica Reactivity," *Durability of Concrete*, Proceedings of the Second CANMET/ACI International Conference, SP-126, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich., pp. 973-987.

Taylor, H. F. W, 1990, *Cement Chemistry,* Academic Press, San Diego, Calif., 475 pp.

Vaysburd, A. M.; Emmons, P. H.; McDonald, J. E.; Poston, R. W.; and Kesner, K. E., 1999, "Performance Criteria for Concrete Repair Materials, Phase II Summary Report," *Technical Report* REMR-CS-62, U. S. Army Corps of Engineers, Mar., 72 pp.

Watson, P. M., 1996, "Preplaced-Aggregate Concrete," *Aberdeen's Concrete Repair Digest*, V. 7, No. 3, June-July, pp. 148-152.

Weiss, J. W.; Yang, W.; and, Shah, S. P., 1998, "Shrinkage Cracking of Restrained Concrete Slabs," *Journal of Engineering Mechanics*, V. 124, No. 7, July, pp. 765-774.

Whiting, D., 1981, "Rapid Determination of the Chloride Permeability of Concrete, Final Report," *Report* No. FHWA/RD-81/119, Federal Highway Administration, Washington, D.C., 166 pp.

APPENDIX A—CURRENT INDUSTRY ISSUES AND CONCERNS

Selecting materials for concrete repair is a complex process. New materials and variations on existing technologies appear on a regular basis. Ashby (1992) reported that somewhere between 40,000 and 80,000 different materials are available. Qualities that are desirable for materials used in new construction can be irrelevant or even detrimental in repair materials. Materials that are more rigid, or greatly different in compressive strength or permeability than the concrete being repaired, may not be compatible with the existing structure or with the repair procedure being used, and can contribute to repair failures. The selection of materials used for repair should be based on different criteria than those used for new construction.

A.1—Material test methods and reporting of test data

For specifiers and applicators to make an informed decision regarding the selection of repair materials, accurate information should be available on the relevant material properties for the materials being considered. This implies that relevant prop-

erties should be identified, and that appropriate test methods should be used to measure and compare these properties.

Information on material properties is typically furnished by the material manufacturer or supplier; however, different manufacturers frequently report data for similar materials in ways that make the specifier's and applicator's decision more difficult, if not impossible. There are several aspects of this problem. In some cases, there is no appropriate test method currently approved or even available for certain materials, material properties, or field-application conditions. For instance, there is no standardized test method for tensile creep (Neville 1996), which can reduce the buildup of stresses due to restrained shrinkage, thereby possibly reducing cracking in the repair material. Another example is the restrained shrinkage of repair materials. While there are currently several test methods for measuring the restrained shrinkage of repair materials, very few have been approved by industry organizations. AASHTO has adopted PP 34 as a provisional standard, and several other similar test methods are under development (Weiss et al. 1998).

As a result, materials manufacturers and suppliers are left with several options, all of which can result in misleading information for the user: use existing test procedures that may not be representative of actual repair conditions or may not present their product favorably; use nonstandard, modified test methods; or develop new test methods. Various manufacturers may modify standard test methods in different ways, or each may use different, new test methods. In some instances, the modified or new test procedures can be developed in such a manner to present certain materials more favorably or to show better performance under certain specific conditions. Specifiers and applicators are then left with reported properties based on different test methods that cannot be compared or evaluated.

Manufacturers sometimes report material test data per standard test methods, but with one or more of the parameters of the standard test modified. In this case, the testing was basically performed following the general guidelines of the standard test, but some aspect of the test was modified. In most cases, the modification and the reason for the modification are not described on the data sheet. Given the number of different manufacturers, with each modifying the testing procedures independently, direct comparison based on published test results is often impossible.

An example of a modified test procedure involves the curing regimen followed when testing the length change of a sample material. ASTM C 157/C 157M describes two curing procedures: water cure for 14 days, then air cure for 14 days, or water cure for 28 days. Neither of these curing methods accurately reflects field curing of concrete replacement materials. On the job site, top concrete replacement may be moist cured for 7 days, but many concrete replacements are moist cured for a short time or not at all and then treated with a curing compound. The individual manufacturer typically tests and reports its material using whatever curing regimen the manufacturer recommends for the use of the particular product. Therefore, whenever a particular material is specified based on given shrinkage data, the specifier most likely does not realize the curing regimen required to achieve the given performance. Actual performance of the material may be quite different under different conditions.

A primary concern is the length of time that is required for various consensus organizations to review and approve new or modified test methods that are suited to newly developed materials or new uses for existing materials. It would be desirable if the professional organizations could be encouraged to expedite their review and approval procedures for repair materials. From the aforementioned perspective, it is extremely important for all manufacturers to publish test data using identical testing methods. As a step in this direction, ICRI discusses and recommends specific modifications to existing standard test methods (ICRI 1996). Also, the ICRI Repair Materials and Methods Committee is developing a standard data sheet protocol for repair materials, which evolved from a USACE study to develop performance criteria for cement-based repair materials. Until more suitable industry test methods are available, however, Committee 546 recommends all products be tested following recognized and appropriate test methods, standardized where possible, and the results made available to users. A useful compromise would be for the manufacturers to publish data from the standard tests in both unmodified and modified forms, indicating specifically the nature of and the reason for the modification as appropriate. Alternatively, manufacturers could agree on standard modifications to existing test procedures or new tests to be used within that industry. This information would give the specifier and applicator an opportunity to make the best selection of a repair material, and would still allow the manufacturer to present the test results appropriate for the product and application recommendations.

A.2—Curing of repair materials and manufacturers' reported test results

Curing is beneficial for the development of desirable properties with cementitious materials. ACI 308R discusses the curing of concrete. Adequate curing of repairs can be difficult and is sometimes neglected. In particular, for overhead and vertical repairs, curing methods such as the use of water spray or fog may not be practical, and the application of certain membrane-forming curing compounds could affect the appearance, properties, or both, of the completed repair. Providing adequate curing of cementitious repairs is a concern on many repair projects and can be a significant problem for architectural concrete repairs. Development of new curing methods and materials for cementitious repair materials is needed, but through proper use of existing methods, it is possible to achieve an effective cure.

Prepackaged repair products usually report hardened properties of the material, such as compressive strength and permeability, based on laboratory-cured samples. Field curing of concrete replacements may deviate significantly from laboratory curing conditions, resulting in different material properties. Warnings and clear instructions for curing are needed in application instructions and on packages of repair materials. It would be useful for specifiers and applicators if material properties were reported for laboratory-cured

samples and for samples cured under approximate field conditions.

A.3—Product limitations and warnings

Generally, prepackaged repair materials are marketed for use within narrow application limits. Most product manufacturers list some restrictions on where and how their products are to be applied. Limitations may include the depth of the repair or the orientation of the repair (that is, top horizontal, vertical, or overhead). The specifier and the applicator should be aware of these limitations.

Products often contain ingredients that are intended to overcome naturally-occurring limitations of cement-based materials. Product formulations and additives to overcome shrinkage (plastic and drying), to increase setting time, to provide high early strength, to enhance bond, or to inhibit corrosion are common.

Although there is no current requirement for manufacturers to disclose the ingredients that make up their products, perhaps there should be. There are no miracle materials; when ingredients are added to enhance a given property, there is usually a corresponding downside. For example, gypsum- or ettringite-forming additives can accelerate set time and early strength gain, but may reduce durability, resulting in poor performance history in moist environments. Some expansive agents, such as ettringite, can expand beyond a desirable limit in moist environments. Some moisture-sensitive bonding agents redisperse, and can degrade in a moist environment at pH values greater than 8. In some cases, the specifier or applicator may need special expertise to successfully use a certain material. These issues become concerns when specifiers and applicators are not adequately informed about the presence or effect of the ingredients in the repair materials.

Prepackaged cementitious repair materials generally absorb moisture and degrade over time, especially in humid climates. Many suppliers do not adequately moisture-proof the containers nor do they make it easy for the user to determine if the shelf life has expired, with the result that the applied product may not develop its reported potential properties. Products should be properly packaged, and storage requirements and shelf life should be clearly labeled.

A.4—Standardized industry acceptance

Another issue facing the concrete repair industry is how products and materials are brought to the market and accepted for widespread use. There are entities that have been put into place for product evaluation. The burden of additional costs for complete evaluation and approval of new materials, however, has been poorly accepted by the marketplace. “There is no single authority or approval board to validate new technologies. We should rely on the current systems of codes and standards to document industry approval of new technologies and/or application methods…a laborious process that takes 10 years on average to complete” (Shydlowski 1998). It is frustrating for material manufacturers to create a new product with improved properties and then face industry resistance to its use for many years. On the other hand, there have been failures of new products that have been introduced in the market without adequate testing, and specifiers and applicators are understandably reluctant to try a new product with no track record instead of an existing product that has been successfully used for a number of years. Exaggerated claims by some manufacturers encourage this reluctance. There is a glaring need to accelerate improvements in materials technology and characterization methods.

A.5—Repair material bond

Most repairs are bonded to the substrate concrete. Therefore, the adhesive bond between the repair material and the substrate concrete is critical to the satisfactory performance of the repair; one of the most common causes of repair failures is inadequate bond of the repair material. Some studies have shown that bond is primarily a function of the substrate quality, the surface preparation, and the application of the repair material (Silfwerbrand 1990). Others argue that the studies have involved small test specimens instead of large repair areas, and that a bonding agent is needed to ensure bond over large areas. Yet extensive experience has indicated a history of successful repairs without the use of bonding agents. Also, some bonding agents deteriorate the bond when exposed to moisture in service or inhibit the bond when used incorrectly. More information is needed on the key factors to achieve adequate bond under different conditions.

A.6—Corrosion reduction

Concrete deterioration due to reinforcing steel corrosion is a common reason for performing concrete repairs. The repairs usually do not remove all of the deteriorated concrete, nor do they stop corrosion of the reinforcing steel. Many repair programs do not include a cathodic protection system, and thus only extend the service life of a structure; they do not stop or eliminate corrosion activity altogether. There are a number of repair options that are intended to reduce corrosion activity in the concrete replacement, in the existing structure away from the concrete replacement, or both. Some options include coating exposed reinforcing bars with materials such as epoxies and polymer-cement, cement-based mortars; improving the repair concrete with admixtures, such as silica fume, a polymer, or a steel corrosion inhibitor; and protecting the existing concrete with a surface-applied corrosion inhibitor, a coating, or an overlay. Each of these options has potential benefits, risks, and associated costs.

The use of chemical corrosion inhibitors in concrete repair is recent; they were introduced in the early 1990s. The effectiveness and life expectancy of these materials is unknown at this time, and likely vary considerably with different types of inhibitors and site conditions. Users report a wide variation in their effectiveness, and this presents the question as to what parameters relate to successful use. Studies of their effectiveness in new concrete at the Virginia DOT (Sprinkel and Ozyildirim 1998) have extended the question to repair materials as well. If manufacturers are adding corrosion inhibitors to prepackaged materials or are selling corrosion inhibitors for topical treatment to the surface of the concrete,

the corrosion inhibitor type, recommended uses, constraints, and anticipated effectiveness should be published in their product literature.

Public agencies and private owners spend large sums of money repairing and addressing concrete deterioration due to reinforcing steel corrosion, and much research has been performed to evaluate various repair options. Unfortunately, the results of the research are sometimes conflicting, and all of the repair options have limited effectiveness. Additional research and field trials are needed to further evaluate existing repair options and to evaluate new materials.

These concerns should not infer that the available products should not be used, only that the specifier and user should be aware of the limitations and the benefits. Choosing a repair material is a compromising process. It should be an informed compromise.

A.7—Structural repairs

Perhaps the most misused term in the concrete repair industry today is structural repair. A structural repair is a repair that is intended to satisfy a deflection or strength (load-carrying) requirement of a structural member. Unless the existing loads are temporarily removed from the member, such as by jacking, shoring, or removal of the existing loads, the existing loads are redistributed in the remaining concrete and reinforcement and, at best, the concrete replacement only shares in additional loads that are applied after the concrete replacement has set. These additional loads are commonly only a fraction of the pre-repair loads; this means the vast majority of concrete replacements are nonstructural by this definition.

Many repair materials are marketed for structural repairs. This may mean they have different mechanical properties from nonstructural repair materials, such as a higher modulus of elasticity. As discussed in Chapter 3, this may be detrimental for the proper performance of nonstructural repairs.

Repairs that are truly structural in nature are intended to enhance or restore the integrity of a structure and should only be designed by a qualified structural engineer. In this case, the specifier should first ensure that the member to be repaired is unloaded an amount required to achieve the desired structural performance. An appropriate repair material should then be selected. For structural repairs, a repair material with a modulus of elasticity approximately equal to that of the substrate concrete is normally selected.

A.8—Ongoing developments

Over the years, the concrete industry has gradually come to understand that new concrete construction and the repair of existing concrete structures are distinctly different disciplines. Recognizing the differences in design, materials, and methods is one aspect, and providing qualified professionals and materials of appropriate quality is another. In 1998, a special Technical Activities Committee—Repair and Rehabilitation Committee (TRRC)—was formed by ACI to address the unique issue of repair. The assignment given to the TRRC was to develop and carry out a 5-year strategic plan for repair and rehabilitation within ACI. The mission of the TRRC is to provide leadership and technical guidance within ACI on issues of concrete repair, rehabilitation, maintenance, protection, and strengthening. A second near-term objective is to survey current ACI committee activities and identify those related to repair and rehabilitation.

ICRI is an organization of engineers, material suppliers, and contractors that specialize in the repair of concrete. This organization has been instrumental in promoting good repair practices and the use of proper repair materials. ACI and ICRI should continue to promote concrete repair as a significant area of concrete practice.

As the concrete repair industry continues to grow and more specialty professionals and suppliers join in, many of these issues and concerns will be addressed.

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Guide for the Selection of Materials for the Repair of Concrete

The AMERICAN CONCRETE INSTITUTE

was founded in 1904 as a nonprofit membership organization dedicated to public service and representing the user interest in the field of concrete. ACI gathers and distributes information on the improvement of design, construction and maintenance of concrete products and structures. The work of ACI is conducted by individual ACI members and through volunteer committees composed of both members and non-members.

The committees, as well as ACI as a whole, operate under a consensus format, which assures all participants the right to have their views considered. Committee activities include the development of building codes and specifications; analysis of research and development results; presentation of construction and repair techniques; and education.

Individuals interested in the activities of ACI are encouraged to become a member. There are no educational or employment requirements. ACI's membership is composed of engineers, architects, scientists, contractors, educators, and representatives from a variety of companies and organizations.

Members are encouraged to participate in committee activities that relate to their specific areas of interest. For more information, contact ACI.

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