ANSWERS FROM ACI'S CONCRETE KNOWLEDGE CENTER

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In this spirit of cooperation, ICRI is publishing the following answers to Technical Questions, developed by ACI staff and committees. These Technical Questions can be found on ACI's Web site in the Concrete Knowledge Center.

The Concrete Knowledge Center, which can be accessed from ACI's home page at **www.concrete.org**, contains discussions of concrete-related techniques, answers to commonly asked questions, and case studies. Topics include decorative concrete, floor construction, formwork design, placement techniques, repair procedures, residential construction, sustainability issues, and testing methods.

CEMENT-BASED REPAIR MATERIALS

This frequently asked question (FAQ) is reported by ACI Committee 364, Rehabilitation. The FAQ and response have passed through ACI's full consensus process, including review by the TAC Repair and Rehabilitation Committee.

Q. What physical properties of cement-based repair materials are important to minimize cracking in repairs?

SIGNIFICANCE

One of the principal factors assuring the durability of a concrete repair is its resistance to cracking. Cracking of repair materials is typically the result of dimensional incompatibility between the repair material and the concrete substrate. Cracks in the repair allow aggressive external agents direct access into the repair area and to the surface of the reinforcement, enhancing development and propagation of reinforcement corrosion, and the deterioration of the repair and concrete substrate.[1]

A. All properties that affect the dimensional behavior of a repair material will have some influence on its resistance to cracking. Dimensional compatibility is defined by ICRI[2] as "a balance of dimensions, or volumetric stability, between a repair material and the existing substrate." Material properties that affect dimensional compatibility include drying shrinkage, tensile strength, modulus of elasticity, coefficient of thermal expansion, and creep.[3,4]

DISCUSSION

Structural and nonstructural repairs are considered in this discussion. Structural repairs can be defined as load-carrying repairs. For example, repairs to structural elements such as columns that will be subject to applied loads must be able to accommodate these loads. Many repairs to load-carrying elements, however, are cosmetic repairs that reestablish the original configuration. Such repairs are not likely to be subjected to significant loads because it is difficult and expensive to unload the element prior to repair. Repairs that are not subject to externally applied loads are defined as nonstructural.

Cracking caused by restrained contraction occurs when the induced stress exceeds the tensile strength of the repair material. External and internal restraint conditions that induce tensile stresses that can lead to cracking are discussed in ACI 207.2R.[5] Restrained contractions that can induce cracking are typically caused by shrinkage and temperature volume changes. In the case of cementitious materials, these volume changes may occur individually or in combination and while the material is in either a plastic or hardened state. The composition and physical properties of a repair material that affect its resistance to cracking are discussed in the following. Refer to ACI 224.1R[6,7] for additional information on causes and control of cracking.

Composition—Constituent materials and mixture proportions can have a significant effect on dimensional stability and resistance to cracking. Factors that should be considered when selecting or proportioning cement-based repair materials include:

- The most important controllable factor affecting drying shrinkage is the amount of water per unit volume of material; therefore, the water content should be as low as possible;
- The cement content should be as low as practical to minimize the paste volume and reduce heat rise;
- In general, the water-cementitious material ratio (*w/cm*) should not exceed 0.4;
- Mixtures should contain the maximum practical size and volume of coarse aggregate; and
- The modulus of elasticity of a cementitious material is directly proportional to the aggregate modulus; therefore, a lower modulus aggregate is desirable for protective repair materials.

Tensile strength—The tensile strength, determined in accordance with CRD-C 164,[8] should be a minimum of 400 psi (2.8 MPa), a tensile strength that would be expected for conventional concrete with a compressive strength of approximately 5000 psi (35 MPa). The easiest way to improve the resistance of cementitious materials to cracking would be to achieve substantially higher tensile strength. While higher tensile strengths would improve resistance to cracking, there are limits to what can be achieved in cement-based materials. Because it is virtually impossible to substantially increase the tensile capacity of a cement-based material, the primary goal should be to reduce tensile stresses to minimize cracking.

Compressive strength—Concrete repairs are broadly classified as structural or nonstructural. Both types of repairs must provide protection to the concrete substrate and embedded reinforcement; however, nonstructural repairs are not intended to carry loads. The compressive strength of a repair material should be similar to the strength of the existing concrete. Generally, there is no advantage to having compressive strengths in excess of 4000 psi (28 MPa) for nonstructural repair materials. In fact, it is generally agreed that high-strength repair materials are more prone to cracking because of higher stresses developed from restrained shrinkage and lower stress relaxation because of typically higher moduli and lower creep. In addition, the use of rapid-setting materials to achieve high early strength often leads to increased cracking because of higher early-age volume changes, increased stiffness, and less creep.

Modulus of elasticity—The modulus of elasticity of the material for structural repair should be similar to that of the existing concrete. The modulus of elasticity for nonstructural repair materials, determined in accordance with ASTM C469-02e1,[9] should typically be specified to not exceed 3.5×10^6 psi (24 GPa). The modulus of elasticity of repair materials can be reduced with lower compressive strengths and aggregate with a lower modulus of elasticity.

Coefficient of thermal expansion—Thermal compatibility is most important in environments that are frequently subject to large changes in temperature, especially large repairs and overlays. The coefficient of thermal expansion should be similar to that of the concrete substrate. In general, the coefficient of thermal expansion, determined in accordance with CRD-C 39,[10] should not exceed 7 millionths/°F (13 millionths/°C).

Drying shrinkage—The drying shrinkage of repair materials, determined in accordance with ASTM C157/C157M-08,[11] modified as described in the following, should not exceed 0.04 and 0.1% at 28 days and 1 year, respectively.

Fig. 1: Typical comparator for length-change measurements

The standard specimen size is 3 x 3 x 11.25 in. (76 x 76 x 275 mm) for concrete, mortar extended with aggregate, and mortar. This specimen size allows comparison of mortar and concrete as opposed to using 1 x 1 x 10 in. (25 x 25 x 275 mm) specimens that show more severe volume changes because of their higher surface-to-volume ratio. Specimens are removed from the mold at 24 ± 1/2 hours and the initial comparator reading is made immediately. For rapid-hardening materials, demold specimens and make initial comparator readings at 3 ± 1/4 hours. Specimens are then stored in the air at 73.4 ± 3°F (24.0 ± 1.7°C) and 50 ± 4% relative humidity (RH).

Subsequent comparator readings (Fig. 1) should be taken at 3, 7, and 14 days; 1 and 2 months; and periodically thereafter until 90% of the ultimate drying shrinkage is reached. Ultimate shrinkage should be determined in accordance with ASTM C596-09.[12]

Drying shrinkage of a repair material is affected by a number of factors, including temperature, relative humidity, absorptivity of the substrate, and ratio of volume to exposed surface (ACI 209R).[13]

Wet curing does not eliminate drying shrinkage; it merely delays moisture evaporation and associated shrinkage. Proper curing, however, can have a beneficial effect on the development of material properties, such as tensile strain capacity, that will reduce the risk of cracking. The tensile strain capacity of repair materials is very sensitive to the rate at which strain is applied or, in other words, to the rate at which drying occurs. Rapid drying causes a rapid strain rate and minimizes strain relaxation resulting from creep of the material.

Creep—Relaxation through tensile creep reduces the stresses induced into a repair material by restrained drying shrinkage. The reduction in tensile stress within a repair material will enhance the crack resistance of nonstructural repairs. Test results[14] show that tensile creep capacity is quite dependent on material composition, often more so

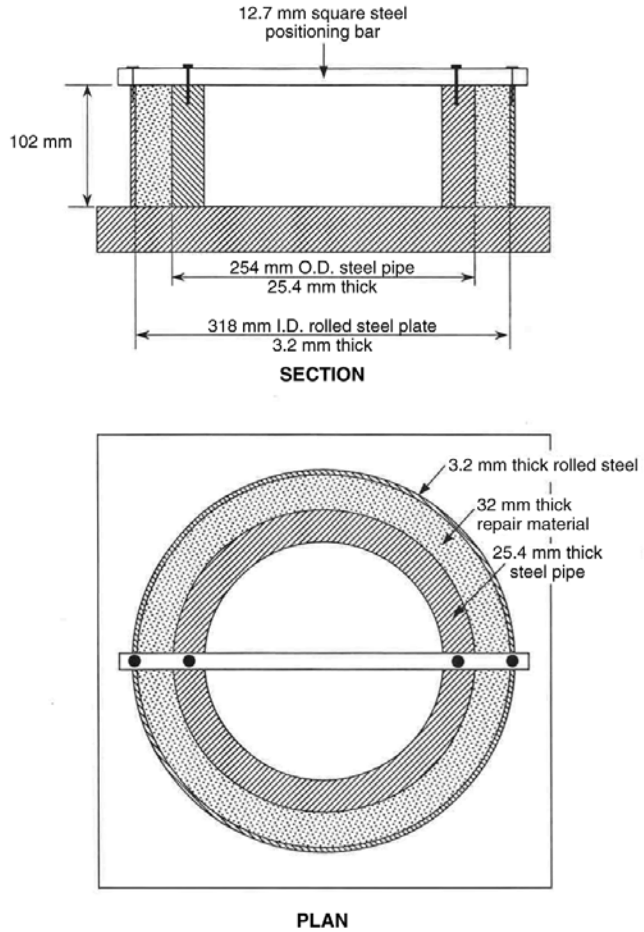

Fig. 2: Ring test mold and test specimen. Note: 1 mm = 0.0394 in.

Fig. 3: Typical ring test specimen

than shrinkage. Because a reduction in paste content reduces shrinkage and appears to increase tensile creep, a proper repair mixture should have the lowest practical cement content. Also, creep of cement-based materials is inversely proportional to modulus of elasticity and compressive strength; therefore, high-strength, high-modulus materials are undesirable for nonstructural concrete repairs.

Restrained shrinkage—A material's sensitivity to cracking caused by restrained volume changes should be evaluated in a ring test (Fig. 2). When tested in this manner, a material should not exhibit cracks within the first 14 days after the 2-day curing period and the implied strain should not exceed 0.1% at 1 year. A provisional test method for determining restrained shrinkage with the ring method is given in AASHTO PP34-99.[15] Other dimensions and degrees of restraint for variations of the ring test continue to be developed to further refine the AASHTO method.[16,17]

In the ring test, a repair material is cast around a 10 in. (254 mm) diameter steel pipe with a 1 in. (25.4 mm) wall thickness. The repair section is 1.25 in. (32 mm) thick and 4 in. (102 mm) high. The material should be mixed, placed, and consolidated as recommended by the manufacturer. The specimens are covered with plastic for the first 24 hours after casting. After demolding, the top surface of the specimen is sealed and the specimens are moist-cured for 48 hours. After completion of the recommended curing period, specimens are allowed to air dry for a minimum of 60 days under standard laboratory conditions.

Specimens should be monitored daily for cracks and crack widths should be measured with a precision of 0.001 in. (0.04 mm). Crack widths should be measured periodically at quarter points and midheight of the specimen (Fig. 3) to obtain an average crack width. Implied strain is computed by adding the average widths of all cracks in a specimen, then dividing the total crack width by the circumference of the test specimen.

Performance criteria—While the results of a comprehensive investigation[3,4] indicated a general lack of correlation between individual material properties determined in the laboratory and field performance, the study indicated that it is possible to predict field performance based on the combination of material properties discussed herein. Performance criteria proposed by the U.S. Army Corps of Engineers are presented in Table 1. The relative importance of individual properties will vary depending on application and service conditions; therefore, the requirements should be modified as necessary to achieve compatibility with the existing substrate.

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2. ICRI, "Concrete Repair Terminology," International Concrete Repair Institute, Rosemont, IL, Mar. 2002, 52 pp.
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TABLE 1: TYPICAL PERFORMANCE CRITERIA FOR REPAIR MATERIALS[3]

Property	Test method	Requirement
Tensile strength, minimum 28 days	CRD-C164[8]	400 psi (2.8 MPa)
Modulus of elasticity, maximum	ASTM C469-02e1[9]	3.5×10^6 psi (24 MPa)
Coefficient of thermal expansion, maximum	CRD-C39[10]	7 millionths/°F (13 millionths/°C)
Drying shrinkage, maximum -28 days -1 year	ASTM C157/C157M-08[11] (Modifications described herein)	400 millionths 1000 millionths
Restrained shrinkage -cracking -implied strain at 1 year, maximum	Ring method, described herein	No cracks within 14 days 1000 millionths

Materials: Performance Criteria–Summary," *Concrete International*, V. 24, No. 1, Jan. 2002, pp. 37-44.

5. ACI Committee 207, "Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete (ACI 207.2R-95 [Reapproved 2002])," American Concrete Institute, Farmington Hills, MI, 1995, 26 pp.
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9. ASTM C469-02e1, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," ASTM International, West Conshohocken, PA, 2002, 5 pp.
10. CRD-C39, "Test Method for Coefficient of Linear Thermal Expansion of Concrete," *Handbook for Concrete and Cement*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
11. ASTM C157/C157M-08, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," ASTM International, West Conshohocken, PA, 2008, 7 pp.
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13. ACI Committee 209, "Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures (ACI 209R-92 [Reapproved 1997])," American Concrete Institute, Farmington Hills, MI, 1992, 47 pp.
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NONSHRINK REPAIR MATERIALS

This FAQ is reported by ACI Committee 364, Rehabilitation. The FAQ and response have passed through ACI's full consensus process, including review by the TAC Repair and Rehabilitation Committee.

Q. What does it mean when a prepackaged repair material is labeled "shrinkage compensating" or "nonshrink"?

SIGNIFICANCE

Many proprietary repair materials are described as "shrinkage compensating" or "nonshrink." In most cases, the manufacturers' data sheets do not explain the meaning of such terms. Given the severe restraint conditions typically provided by the concrete substrate, accurate expansion and shrinkage data are essential for selection of materials that will provide durable repairs.

A. The terms "shrinkage compensating" and "nonshrink" are intended to describe materials that exhibit no contraction or controlled expansion. In practice, however, these terms are of limited use in the selection of repair materials without supporting test data on time-dependent volume changes.

DISCUSSION

Moisture loss is practically unavoidable in cement-based materials that are exposed to a RH less than 100%. This moisture loss results in drying shrinkage and volume changes within the material. In addition to shrinkage that occurs because of drying, the hydration reactions will cause some chemical shrinkage that is unavoidable. Consequently, significant efforts have been made to counteract the shrinkage phenomenon and its undesirable effects, such as tensile stresses and cracking. Expansive cements were first introduced half a century ago to produce so-called "shrinkage-compensating" concretes.

"Shrinkage compensating" is defined in ACI 116R-00 as "a characteristic of grout, mortar, or concrete made using an expansive cement in which volume increases after setting, if properly elastically restrained, induces compressive stresses which are intended to approximately offset the tendency of drying shrinkage to induce tensile stresses."[1] In these materials, a chemical agent added to the cement reacts during curing to produce an expansive compound, resulting in a net volume increase of the material. The dosage of expansive agent has to be selected such that the initial expansion will offset subsequent shrinkage, as depicted in Fig. 1.

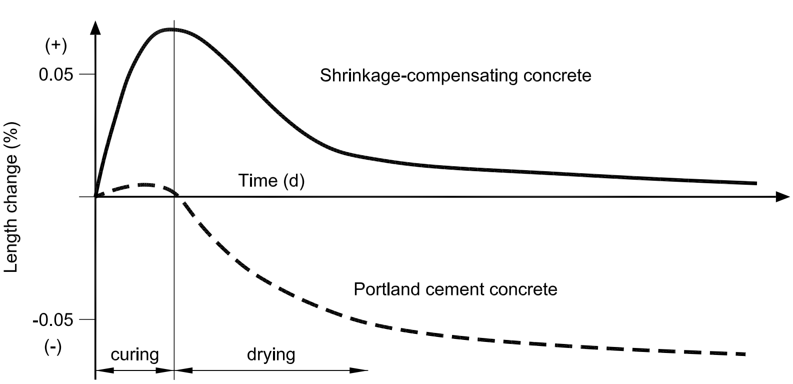

Fig. 1: Typical length change characteristics of shrinkage-compensating and portland cement concrete

The shrinkage-compensation process for repair materials is similar to that for shrinkage-compensating concretes (SCCs). The latter is often made with Type K cement (ASTM C845-04[2]) and sometimes with the use of other types of expansive agents added during the mixing operations, generally calcium sulfoaluminate-based (CSA) or lime-based (CaO). The various proprietary shrinkage-compensating repair materials available can differ significantly in composition, especially when it comes to the nature of the expansive compound. In addition to the aforementioned CSA-based and CaO-based agents, other additives such as gas-liberating agents (nitrogen, hydrogen, and oxygen) and diols (dihydric alcohols) are also used. Some dual-action materials even contain two forms of expansive agents; for instance, one agent that produces a gas to counteract shrinkage occurring while the material is still in a plastic state, and another that leads to the formation of a compound that produces expansion in the hardened state.

The term "nonshrink" is often, if not always, used in lieu of the probably more suitable expression "shrinkage compensating." Hydraulic-cement nonshrink grout is defined in ASTM C125-03[3] as "a hydraulic-cement grout that produces a volume that, when hardened under stipulated test conditions, is greater than or equal to the original installed volume, often used as a transfer medium between load-bearing members." There will be some shrinkage as long as cementitious materials are part of the system; thus, strictly speaking, a cement-based material cannot be "nonshrinking."

The term is used by many manufacturers, however, to describe the shrinkage-compensating behavior of their materials. It is also used in ASTM C1107-02[4] for packaged dry hydraulic-cement grouts. Whether the term is misused or not is irrelevant herein. It is important to know, however, that when a prepackaged material is labeled as "nonshrink," it means that during the life of the material, under given environmental conditions, the dimensional balance (expansion minus shrinkage) is supposed to remain positive; there should be no net contraction resulting from drying (refer to Fig. 1). It does not mean that there will be no volume changes.

Because the induced expansion and shrinkage are generally not synchronous, the effectiveness of a shrinkage-compensating system is dependent on restraint during the expansive process to produce a compressive prestress that will decrease with subsequent shrinkage. In new construction, a minimal amount of reinforcement is used to provide this restraint, as recommended in ACI 223-98.[5] There is no such provision for repair materials, and it certainly requires some attention, especially in the case of bonded surface repairs without reinforcement where the restraint is provided by simple adhesion with the substrate and, depending on the configuration of the repair (partial-depth versus overlay work), by abutment to the vertical edges.

Information on the dimensional behavior of "shrinkage-compensating" or "nonshrink" repair materials is generally insufficient or absent from manufacturers' data sheets. This lack of information is due, in part, to the absence of explicit standardized test procedures and specifications for "shrinkage-compensating" materials. ASTM C1107 requires that the height change of moist-cured, hardened hydraulic-cement grout be within the range of 0 to 0.3% when tested in accordance with ASTM C1090-01.[6] In the case of rapid-hardening cementitious materials for concrete repairs (ASTM C928-00[7]), the maximum allowable increase in length change is 0.15% after 28 days in water and the maximum allowable decrease is –0.15% after 28 days in air. This range for maximum allowable expansion and contraction is so permissive that most materials fall between the limits. Also, there are no requirements for rate of volume change for rapid-hardening cementitious repair materials. The rate of volume change is important in repairs and is addressed for other types of materials in ASTM C845-04[2] and C1107-02[4].

As illustrated in the following examples, which show two typical data sheets, the information provided to the customer can be quite confusing. In the absence of appropriate information, the engineer should consult the manufacturer to determine the suitability of a given material in a given situation.

EXAMPLE 1: MATERIAL A

Description: One-component, polymer-modified, fast-setting, nonshrink repair mortar. *(ASTM C1107 grout terminology; however, ASTM C1090 is not the test method cited.)*

Use: Rapid structural and cosmetic repairs to concrete and beams and restoring disintegrated surfaces of old concrete and masonry.

Properties: 28-day shrinkage/50% RH (ASTM C490-04[8]): –0.10%. 28-day expansion/100% RH (ASTM C490): 0.03%. Curing: Moist-cure for less than 1 hour. *ASTM C490 is the standard practice for use of the apparatus to determine length change by other test methods. It is not an appropriate reference for data reporting, as no curing cycle, demolding time, or alternative sample dimension are described and no rate of volume change is mentioned. How can a material be classified as "nonshrink" when the shrinkage at 28 days is 0.10% and the net volume change is –0.07%? Is the volume change complete at 28 days?*

EXAMPLE 2: MATERIAL B

Description: One-component, shrinkage-compensating, fast-setting, polymer-modified, cement-based profiling mortar.

Use: Leveling and resurfacing distressed concrete and horizontal and vertical surfaces.

Properties: 28-day shrinkage (ASTM C157/C157M-04[9] modified): 0.10%. Curing: Water-based curing compound or moist-cure for 2 days minimum. *Without a description of the modifications to the ASTM C157 method, the shrinkage data given is meaningless. There is no expansion data reported. Was the curing regimen described used in determining the shrinkage data reported?*

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SELECTING REPAIR MATERIALS

Q. I have a crack in a foundation wall that starts from the corner of a rectangular penetration and runs almost vertically down the height of the wall. After a heavy rain, water leaks into the foundation through the crack. When contacted about needed repairs, one contractor recommended injecting epoxy into the crack, and another recommended injecting polyurethane. Which one will give the best repair?

A. Before investing in a crack repair, check the drainage conditions near the penetration. The backfill may have settled over time, leaving a depression that collects water and results in leakage. This can be corrected by filling the depressions with soil. It's also possible that the original ground slope for the area near the penetration was either too shallow, or perhaps even sloped toward your building instead of away from it. This may require more extensive earthwork to provide the minimum 1:6 slope for a minimum of 10 ft (3 m) away from the wall recommended in ACI 332.1R-06.[1] Finally, check to make sure that if gutters are present, the horizontal extensions for downspouts carry water at least 5 ft (1.5 m) away from the foundation wall.[2]

If the crack still leaks, other action is needed. The crack you describe was likely caused by restrained lateral shrinkage of the concrete basement wall. This shrinkage usually causes tension stresses that are uniform through the thickness of the wall. At changes in the height or thickness of the wall, such as windows or doors, these tensile stresses become concentrated and often result in cracks. Because the tensile stresses in the wall are uniform through the thickness, the wall will crack all the way through and allow water to penetrate.

Information about selecting concrete repair materials can be found in ACI 546.3R-06, "Guide for the Selection of Materials for the Repair of Concrete."[3] Both repair materials can stop the leaking water problem. Epoxy injection will form a structural repair that is stronger than the concrete but not very flexible. If the shrinking continues or the crack is still opening for other reasons, the stresses will build up again, and a new crack is likely to form adjacent to the first crack or at the opposite corner of the penetration. Many epoxies used for injecting cracks don't bond well to wet or damp concrete, which may require you to wait until the crack has dried before making the repair.

Polyurethane chemical grout is not strong enough to form a structural repair, but is more flexible than epoxy, bonds well to wet concrete, and is therefore better for sealing leaking, active cracks that open or close over time. Because the crack you describe runs vertically down the wall, it's unlikely that a structural repair is required, but if there is any question, a licensed professional engineer should be contacted to evaluate the cause of the cracking.

The polyurethane chemical grout used to inject cracks should not be confused with polyurethane sealant applied over the crack. If sealant is applied over the crack on the inside of the wall, water can build up behind the sealant and either push it off the wall or diffuse through the concrete adjacent to the crack.

Q. We have to repair some thin delaminations on a concrete slab. What types of products work best for this application?

A. Table 3.1 in ACI 546.3R-06, "Guide for the Selection of Materials for the Repair of Concrete,"[3] lists common repair materials along with their favorable and unfavorable properties. Table 1 (refer to next page) shows these properties for shallow concrete replacements and overlays from 1/16 to 1 in. (1.6 to 25 mm) thick. In addition to cost, a consideration that can be important but is not covered in the table is aesthetics. Surface repairs are very difficult to blend with the surrounding concrete. If aesthetics are a concern, a thin overlay covering a slab panel or the entire slab may be more appropriate. More information about the materials, their advantages and drawbacks, surface preparation, and proper installation can be found in the full document.

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3. ACI Committee 546, "Guide for the Selection of Materials for the Repair of Concrete (ACI 546.3R-06)," American Concrete Institute, Farmington Hills, MI, 2006, pp. 17-26.

DISCLAIMER

TABLE 1: COMPARISON OF MATERIAL PROPERTIES FOR SHALLOW CONCRETE REPLACEMENTS AND OVERLAYS*

Properties	Materials				
	Cement mortar	Silica-fume mortar	Polymer-cement mortar	Polymer mortar	MAPCM†
Volume stability	● (orange)	● (orange)	● (orange)	● (orange)	●
Elastic modulus	●	●	●	● (orange)	●
Thermal expansion	● (orange)	● (orange)	● (orange)	● (orange)	●
Bond strength	○	●	●	●	●
Tensile strength	○	●	●	●	●
Cohesiveness	○	●	●	●	●
Freezing-and-thawing durability	● (orange)	●	●	●	○
Permeability	○	●	●	●	●
Electrical resistivity	○	●	●	●	●
Resistance to chemical attack	○	●	●	●	● (orange)
Heat deflection or glass transition temperature	○	○	○	● (orange)	○

*● denotes favorable property; ● (orange) denotes unfavorable property; ○ denotes neutral property.

†Magnesium-ammonium-phosphate-cement mortar (MAPCM) is mortar in which magnesium-ammonium-phosphate is substituted for portland or blended cement.