Guide to Materials Selection for Concrete Repair

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

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

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

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

As the concrete industry develops and grows, concrete repair is frequently required; however, with the increasing number and age of concrete structures, frequent deferral of maintenance, and increased public awareness of deterioration and maintenance needs, repair is becoming a major focus of design and construction activities. Although concrete repair is traditionally as much an art as a science, engineers and contractors typically do not receive much formal training in techniques for repair and the performance of repair materials applied to concrete. Personal experience is beneficial, but takes time to accumulate and can be costly in terms of failed repairs. Although this is changing, there is still too little information available to reliably predict the serviceability and durability of repairs. Concrete repairs that fail prematurely result in economic loss and usually require additional repairs.

Due to a 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 and building codes and other regulations, many existing, well-proven products are being reformulated into essentially new products that have limited track records. The user might not be informed of these changes.

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

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

ACI 546R is the first ACI publication devoted entirely to the subject of concrete repair. Its principle emphasis is on techniques for concrete repair with limited information on selecting repair materials. 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 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 depends 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 to:

a) Conduct 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 concealed deterioration, distress, defects, and damage, as well as potential future deterioration and distress;

b) Determine 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; corrosion of the steel reinforcement caused by improper placement; carbonation of the concrete; or chloride ingress into the concrete to the reinforcing steel;

c) Assess the application and service conditions to which the concrete repair material is, or will be, exposed;

d) Determine the repair objectives, including desired service life;

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

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

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

1.3—Objective

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

a) Identification of common repair materials;

b) Discussion of relevant material properties;

c) Lists and discussion of test procedures for measuring these properties;

d) Recommendations of minimum test values or performance levels;

e) Discussion of the importance of specific material properties for various repair applications and service environments.

1.4—Scope

This guide discusses material selection for several types of repairs and materials used in their repair:

a) Concrete replacements, categorized on the basis of the depth and orientation of repair;

b) Overlays, categorized on the basis of their thickness;

c) Crack repairs, categorized on the basis of crack stability, crack width, and other service conditions;

d) Surface sealers and traffic-bearing elastomeric coatings, categorized on the basis of their water and chloride ion permeability;

e) Anti-carbonation coatings, categorized on the basis of their carbon dioxide diffusion;

f) Reinforcing steel coatings, embedded galvanic anodes, concrete bonding agents and procedures, crystalline pore blockers, and surface-applied, penetrating corrosion inhibitors, categorized on their ability to alter and improve various concrete properties.

1.4.1 *Concrete replacement and overlay materials discussed in this guide include:*

a) Portland or blended cement-based mortar and concrete;

b) Portland or blended cement-based silica-fume mortar and concrete;

c) Portland or blended cement-based polymer-cement mortar and concrete;

d) Magnesium-ammonium-phosphate-cement mortar and concrete;

e) Polymer-based mortar and concrete.

1.4.2 *Crack repair materials discussed in this guide include:*

a) Epoxy resin;

b) Methacrylate resin;

c) Polyurethane chemical grout;

d) Polyurethane sealant;

e) Silicone sealant;

f) Silyl-terminated polyether sealant;

g) Polysulfide sealant;

h) Flexible epoxy resin;
i) Polyurea;
j) Strip and seal systems, including preformed flexible sheets;
k) Polymer grout;
l) Polymer-cement grout;
m) Cementitious grout.

1.4.3 *Surface sealer materials discussed in this guide include:*
a) Silanes;
b) Siloxanes;
c) Acrylics;
d) Epoxies;
e) Linseed oil.

1.4.4 *Anti-carbonation coating materials discussed in this guide include:*
a) Acrylics;
b) Methacrylate coating;
c) Polymer-modified cementitious materials.

1.4.5 *Traffic-bearing elastomeric coating materials discussed in this guide include:*
a) Polyurethane systems;
b) Polyurethane-epoxy composite systems;
c) Polyurea systems.

1.4.6 *Reinforcing steel coating materials discussed in this guide include*:
a) Modified cementitious materials;
b) Epoxies;
c) Zinc-rich products.

1.4.7 *Concrete bonding materials and procedures discussed in this guide include:*
a) Preparing a clean, dry substrate;
b) Preparing a saturated surface-dry substrate;
c) Prepare a saturated surface-dry substrate with scrub coat of paste from replacement material;
d) Acrylic bonding agents;
e) Epoxy bonding agents.

1.4.8 *Crystalline pore blockers and surface-applied, penetrating corrosion inhibitors*—These are proprietary products with undisclosed ingredients. This guide discusses these materials on a generic performance basis.

1.4.9 *Summary tables of test methods and test values*—Tables 3.8a and 3.8b present summaries of available test methods and typical test values for concrete replacement and overlay materials; Table 4.7 presents a selection guide for these materials. Tables 5.7a and 5.7b present summaries of available test methods and typical test values for crack repair materials; Table 6.14 presents a selection guide for these materials. Tables 7.5a, 7.5b, and 7.5c present summaries of available test methods and typical test values for surface sealers, anti-carbonation coatings, and traffic-bearing elastomeric coatings; and Tables 8.5a and 8.5b present selection guides for surface sealers and anti-carbonation coatings.

1.4.10 *Safety cautions*—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. Health and safety practices have to be established appropriate to the specific circumstances involved with material use. The applicability of all regulatory limitations have to be determined when selecting repair materials, and material selection and use have to comply with all applicable laws and regulations.

1.4.11 *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 or mass-concrete structures, underwater repairs, and other special repair and service environments, refer to the recommendations of other ACI publications (including those of ACI Committee 350 and ACI 546.2R), industry organizations, and material manufacturers for specific guidance in repair material selection.

1.5—Current industry issues and concerns

Appendix A includes a discussion of a number of current industry issues and concerns, including:
a) Material test methods and reporting of test data;
b) Curing of repair materials and manufacturers' reported test results;
c) Product limitations and warnings;
d) Standardized industry acceptance;
e) Repair material bond;
f) Corrosion reduction;
g) Structural repairs; and
h) Ongoing developments.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

There are no notations used in this guide.

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://www.concrete.org/Tools/ConcreteTerminology.aspx. Definitions provided herein complement that source.

basic portland-cement concrete—a composition of portland cement, fine and coarse aggregates, and water.

concrete replacement—the removal and replacement of damaged or deteriorated concrete, including partial-depth as well as full-depth repairs that are sometimes informally called patches.

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

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

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

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

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

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

CHAPTER 3—PROPERTIES OF CONCRETE REPLACEMENT AND OVERLAY MATERIALS AND THEIR IMPORTANCE

3.1—General

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

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

Most test methods cited in this guide are performed at standard conditions at room temperature in many cases, with standard-sized specimens, so reported properties may not reflect the actual properties of the repair material in various-sized repairs in service conditions.

Chapter 3 discusses properties of concrete replacement and overlay materials, and test methods used to evaluate them. Some test methods are not specifically applicable for certain replacement or overlay materials, or replacement or overlay installations, but are useful for comparison. Because descriptions of the various test methods are brief, referenced standards should be reviewed for details. Material manufacturers should provide test data based on ASTM standards and other standardized test methods. ACI 364.3R and ICRI 320.3R describe many relevant properties and appropriate modifications to standardized test methods suitable for cementitious replacement materials. Refer to Appendix A for further discussion regarding modifications to standard test methods.

3.2—Volume stability

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

Most cementitious materials undergo early shrinkage within the first few hours to days after application. Noncementitious materials, such as those with polymeric binders, tend to be more stable with little or no shrinkage after hardening. These materials, however, are subject to greater volume changes due to temperature variations. Significant changes in 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 providing restraint or confinement, such as by keying it into the substrate concrete. 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 of concrete, mortar, and cementitious materials:

1) ASTM C157
2) ASTM C157, as modified by ICRI 320.3R
3) ASTM C596
4) ASTM C806
5) ASTM C827
6) ASTM C1581

ASTM C157, ASTM C596, and ASTM C806 are test methods that involve monitoring the length of test specimens over time under different curing conditions. A restraining cage with an embedded steel rod is used in ASTM C806 to restrain the specimen expansion. ASTM C827 is a test method that involves monitoring the height of cylindrical test specimens until the specimens harden. ASTM C1581 is a test procedure that involves measuring the strains and observing

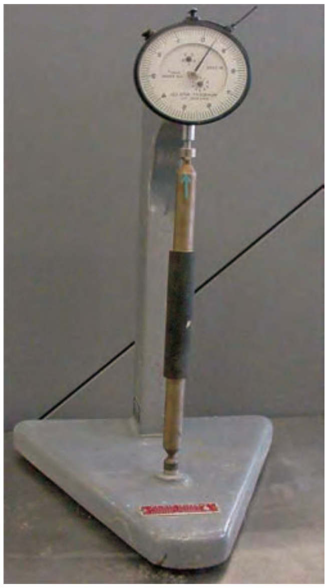

Fig. 3.2.1—Length comparator with standard calibrating rod (ASTM C157). (Photo courtesy of BASF Construction Chemicals, LLC.)

cracking in donut-shaped specimens with inner steel rings. The primary use of these test methods is to provide a relative comparison of various materials when tested in the same fashion. Actual shrinkage experienced in the field will likely differ from shrinkage reported from tests; harsh laboratory test conditions sometimes yield higher shrinkage than that which actually occurs in the field.

3.2.1 *ASTM C157*—The curing and comparator reading regimen in this test method is not applicable for repair mortars and concretes. The test specimens are approximately 11-1/4 in. (285 mm) long and vary in cross section from 1 in. (25 mm) square for mortar specimens to 3 or 4 in. (75 or 100 mm) square for concrete specimens. Initially, the test specimens are stored in a moist room for 24 hours, demolded, and placed in lime-saturated water for a minimum of 15 minutes for mortar specimens and 30 minutes for concrete specimens. Initial length comparator measurements are taken. The specimens are stored in lime-saturated water until they have reached an age of 28 days, when another set of length comparator measurements are made. After these measurements, the specimens are stored in either lime-saturated water or in a drying room, and length comparator measurements are taken at 4, 7, 14, and 28 days (drying room storage only), and 8, 16, 32, and 64 weeks, including the initial 28-day curing period. The length change, in percent, at any age is calculated. Typical shrinkage strains range from 0.02 percent expansion to –0.12 percent shrinkage. The length comparator setup is shown in Fig. 3.2.1.

Neither curing regimen is representative of field conditions for most repair mortars because the initial length-comparator measurement is made at 24 hours, neglecting volume changes that occur within the first 24 hours; extensive wet curing is used, and the specimens are not restrained. In field conditions, bonding repair materials to the substrate concrete provides restraint to shrinkage and an increased exposed surface area, such as shallow or long slender repair geometries, can significantly increase shrinkage.

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

The specimen size has a significant effect on shrinkage results. Different-sized specimens have different surface-to-volume ratios, which will affect the rate of shrinkage (Hansen and Mattock 1966). A 1 in. (25 mm) square specimen shrinks more quickly than 3 or 4 in. (75 or 100 mm) square specimens. If larger specimens are used, it may be appropriate to consider shrinkage at 16 weeks instead of 28 days. Comparison of shrinkage results should always be made using the same specimen dimensions, curing regimen, and storage conditions.

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

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