TECHNICAL GUIDELINES

Prepared by the International Concrete Repair Institute June 2015

Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces

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About ICRI Guidelines

The International Concrete Repair Institute (ICRI) was founded to improve the durability of concrete repair and enhance its value for structure owners. The identification, development, and promotion of the most promising methods and materials are primary vehicles for accelerating advances in repair technology.

Working through a variety of forums, ICRI members have the opportunity to address these issues and to directly contribute to improving the practice of concrete repair.

A principal component of this effort is to make carefully selected information on important repair subjects readily accessible to decision makers. During the past several decades, much has been reported in the literature on concrete repair methods and materials as they have been developed and refined. Nevertheless, it has been difficult to find critically reviewed information on the state of the art condensed into easy-to-use formats.

To that end, ICRI guidelines are prepared by sanctioned task groups and approved by the ICRI Technical Activities Committee. Each guideline is designed to address a specific area of practice recognized as essential to the achievement of durable repairs. All ICRI guideline documents are subject to continual review by the membership and may be revised as approved by the Technical Activities Committee.

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Synopsis

The purpose of this guide is to aid the designer, specifier, contractor, and manufacturer to make rational informed decisions in selecting materials for the repair of concrete surfaces. Its primary focus is on the components and structure of the selection process itself. To assist with the identification and prioritizing of the performance requirements, a detailed section on material properties and test methods has been included. The state of the art of repair material selection has changed a great deal since this document was originally published. Minor changes were added in 2009, although much of the text remains from the original 1996 publication. The adoption of ICRI 320.3R, Guideline for Inorganic Repair Material Data Sheet Protocol; ACI 364.3R, Guide for Cementitious Repair Material Data Sheet; ACI 562, Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings; ACI 546.3R, Guide for the Selection of Materials for the Repair of Concrete; and other documents impacts the content of this document and requires harmonization with these newer documents.

Keywords

Bond strength; constructability; dimensional behavior; durability; materials selection; test methods

This document is intended as a voluntary guideline for the owner, design professional, and concrete repair contractor. It is not intended to relieve the professional engineer or designer of any responsibility for the specification of concrete repair methods, materials, or practices. While we believe the information contained herein represents the proper means to achieve quality results, the International Concrete Repair Institute must disclaim any liability or responsibility to those who may choose to rely on all or any part of this guide.
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4.0 Selecting Repair Materials

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Selection Considerations

Table: Typical Characteristics of Selected Repair Materials

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The Material Selection Process

The selection of a repair material depends on many factors. The evaluation process determines the cause and effect of the damage, deterioration, or design plus construction deficiency such as leakage, settlement, deflection, wearing, spalling, disintegration, cracking, etc. The decision to perform repair is based on a number of factors including whether the structure is salvageable, if the effects are tolerable to have a deferred repair, and what the owner requirements are such as budget, time, and serviceability. Repairs are required to address safety issues, structural catastrophe, use dysfunction, leakage, effects on the environment, aesthetics, preventative maintenance and changes in code requirements.

Once the decision has been made to perform repairs, a condition survey is needed to evaluate, quantify, and document the affected areas. The results of this survey are then analyzed based on the owner considerations such as urgency, cost, expectations, service life, aesthetics and the engineering criteria to include structural requirements, constructability, environment, and serviceability. The repair strategy then balances what alternatives are available for surface preparation, material properties, and application methods. Material selection is only one of the many parts of this decision making process.

Often a specification is used for suppliers, purchasers, and users of materials, products, or services to understand and agree upon all requirements. A specification is a type of a standard which is often referenced by a contract or procurement document. It provides the necessary details about the specific requirements.

Specifications may be written by government agencies, standards organizations (such as ASTM, ISO, CEN, ICRI, ACI, etc.), trade associations, private companies, public corporations, and others. Common specification types are prescriptive, performance, and proprietary specifications.

Prescriptive specifications list what ingredients, quantities of those ingredients, and tolerances for each additive to be used as the recipe for the material formulation. Performance specifications list properties,
methods for determining those properties, and acceptable values or ranges for those properties. Proprietary specifications list specific products or material sources that are acceptable. Combining these types of specifications in construction contracts often causes confusion due to the conflict between what a material should contain, how the material should function when applied, and how the product is represented in the manufacturer’s literature.

If proprietary specification cannot be used as a sole source, often the phrase “or equal” is used. Without the same values and methods used for obtaining the data for both the specified and proposed equivalent material, doubt remains if the alternate material is indeed equivalent as well as if the composition of the proposed alternative is possible to be determined or even relevant. This forms the basis for the increased importance of performance specifications in construction contracts.

Performance based specifications for a class of materials are frequently developed through a consensus organization and can result in the composite of lowest performance of the materials from those members of the standards organization. As knowledge is gained about the relevant properties needed to select a compatible repair material for a specific repair situation, it is hoped that performance based specifications based on the material properties required for the application constraints, the service conditions, and the design properties will become more commonly used in the industry.

Concrete repair materials can be formulated to provide a wide variety of properties. Because the properties affect the performance of the repair, choosing the right material requires careful study. This guide is designed as a tool to help the designer, specifier, contractor, and manufacturer make the best possible decisions in selecting materials for the repair of concrete surfaces. Its primary focus is on the components and structure of the selection process itself. To assist with the identification and prioritizing of performance
requirements, a detailed section on material properties and test methods has been included. Users should note that although there are some references to polymer-based material in that section, the emphasis throughout is on cement-based materials.
Selecting materials for surface repair is a complex process. Not only must constructability and service issues be considered, selection must also be guided by an understanding of the owner’s (user’s) concept, the anticipated service life, applicable codes, and the engineering requirements. It is only after these criteria have been defined and the required material properties identified that the selection of specific materials can be made. Often more than one material or system of materials will satisfy the established requirements. Final selection of materials is based on the relationship between cost, performance, and risk. (See Emmons (1993) for additional information on the material selection process.)

The initial step in the process of producing durable concrete repairs is to determine the cause(s) and extent of existing deterioration. This forensic phase merits separate treatment and is beyond the scope of this document. For further information on structural evaluation see ACI 364.1R*, Guide for Evaluation of Concrete Structures Before Rehabilitation and ICRI 210.4, Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures.

*References cited in this manner are from the ACI Manual of Concrete Practice, American Concrete Institute

The next step in the material selection process is to consider owner requirements, application conditions, and service conditions. These data are needed to develop criteria for determining the material properties which will best meet the engineer’s and owner’s objectives.

Section 1 of this guide includes checklists to help ensure that the most important considerations are addressed.

Section 2 reviews the material properties that should be assessed for relevance on every project. This section also illustrates the likely consequences of omission or of unsuitable choices for each property.
Section 3 works through the process of determining performance requirements and establishing priorities. Rarely, if ever, will a material provide all of the properties a specifier would like to obtain. Prioritizing the desired properties will help ensure the best possible outcome when choices need to be made to achieve the most effective mixture of properties. Examples are provided to assist in relating service and user needs to required material properties.

Section 4 summarizes selection considerations and suggests resources that may help identify materials which provide required properties. A table showing typical properties of the most common repair materials is included.

Concept of Surface Repair

The repair of concrete surfaces involves the construction of a composite material that, unavoidably, will differ from the original concrete (Fig. 1-1). The new composite consists of the following elements:

i. Original concrete substrate prepared to receive repair material.

ii. Interface between existing concrete and new repair material.

iii. New repair material.

iv. Protective or aesthetic treatments.

The selection of a suitable repair material is a process which must consider not only application requirements and durability properties, but, more importantly, it must ensure that the selected material will be compatible with the substrate for the repair to be durable with applicable maintenance.

The design of a repair should consider the compatibility of the repair materials and the materials of the existing structure. Compatibility of repair materials and systems include dimensional compatibility, bond compatibility and durability, mechanical compatibility, and electrochemical and permeability compatibility.
Generally, the intent is to use a repair material or repair system that has physical, mechanical, and other properties that are close to those of the parent material to provide long-term performance. Individual repair materials may have different properties yet will perform satisfactorily when used as part of a repair system. The selection of reinforcement material should consider the durability, performance at elevated temperatures, and ductility. Electrical and chemical reactivity between the repair material, the reinforcement used in the repair, other embedded items, and the existing reinforcement should also be considered. This balance is necessary if the repair system is to best withstand all stresses and strains induced by the total load envelope without distress or deterioration in a specified environment over the expected service life. For detailed discussions of compatibility issues and the need for a rational approach to durable concrete repairs, see Emmons, Vaysburd, and McDonald (1993 and 1994).

Several models for prioritization of repair material selection have been published. Morrisey (2012) provides a forced ranking weighting system to subjectively evaluate the relative importance of repair material properties based on situational factors. Another weighting system was developed at the Iowa Dept. of Transportation (2004). A more detailed review of repair selection and a proposed model is discussed by Do and Kim (2012).

Material incompatibility is a major cause of repair failures. Giving high priority to ensuring compatibility between the repair material and the existing substrate for the anticipated range of service conditions will produce good material selection decisions. Compatibility considerations must include the behavior of the material in both cured and uncured states. The most important material requirement is dimensional behavior relative to that of the substrate to be repaired. The dimensional responses of the repair material are not always identical to those of the substrate, and differential volume changes will cause internal stresses to develop. Typically, these stresses will affect all four elements of the repair composite: the substrate, the interface, the repair material itself, and the protective or aesthetic treatments. High internal stress may result
in tension cracks, loss of load-carrying capability, or delamination, and may contribute to material
deterioration or reduced service life.

Structural Applications

Another difficult challenge is selecting surface repair materials for structural load-carrying applications.
Ideally, the repair material would assume the stress levels and distribution as they existed in the fully
functional member. Repair efficiency is defined as the ratio of stress carried by the repair compared to the
stress carried by the member before deterioration and repair. There are two obstacles to achieving 100%
repair efficiency:

i. How is the repair material loaded initially? Are loads removed from the structure during repair?

ii. How will the dimensional behavior of the repair material affect the level of stress carried by the
repair?

It is unlikely that materials will be found which fill the repair cavity without shrinking during curing, and
behave identically as the substrate in response to loads and changes in temperature and moisture. Repair
priorities established earlier in the planning process may require that trade-offs be made. Material selection
is a process of arriving at informed compromises.

1.0 Project Objectives

Before the material selection process can begin, the specifier will need to identify the following:

i. Cause(s) of Deterioration

Determining the cause(s) of existing deterioration merits separate treatment and is beyond the scope of
this document.

ii. Owner Requirements
The expectations for the project needs to be clearly understood. Expected service life, appearance, structure utilization needs during rehabilitation, and budget are questions that must be addressed at the outset.

### iii. Service Conditions

All components of the load envelope including weather factors, chemical environment, and live loads need to be assessed to identify the physical and mechanical properties needed.

### iv. Application Conditions

Expected weather conditions, access, project time frame, and operating conditions may critically affect material selection.

The checklist which follows will help ensure that many of the most important issues will be considered and resolved at the optimum time before the project is underway.

### Material Selection Checklist

#### Owner Requirements

<table>
<thead>
<tr>
<th>Required appearance:</th>
<th>Yes</th>
<th>No</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repair visible:</td>
<td>___</td>
<td>___</td>
<td></td>
</tr>
<tr>
<td>Crack free:</td>
<td>___</td>
<td>___</td>
<td></td>
</tr>
<tr>
<td>Surface texture:</td>
<td>___</td>
<td>___</td>
<td></td>
</tr>
<tr>
<td>Color considerations:</td>
<td>___</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Repair work interference with the use of the structure:**
Return to service time: __________________________

Expected life of repair: (See ACI 365.1R)

How long: __________________________

Maintenance interval: __________________________

Tolerance for repair failure:

Type of failure:

Cracking: __________

Disintegration: ______

Delamination: ______

Appearance: ______

Effect of failure on:

Health and safety: __________________________

__________________________________________
Process interruption: ________________________________

Structural performance: ______________________________

Environment: ________________________________________

____________________________________________________

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Material Selection Checklist

Service Conditions (See ACI 562 Ch. 5, 6, 7)

Load carrying requirements:

<table>
<thead>
<tr>
<th>Load Carrying Requirements</th>
<th>Yes</th>
<th>No</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead loads:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live loads:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External loading:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheel:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pedestrian:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquids—static:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquids—moving:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil—lateral:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrostatic pressure:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exposure conditions:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Atmospheric gases: □ Yes □ No Type: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concentration: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duration: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Chemicals in contact: □ Yes □ No Type: ______ (See ACI 515.2R)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concentration: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duration: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>UV exposure: □ Yes □ No Type: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concentration: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duration: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Moisture conditions: □ Yes □ No Type: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Temperature extremes: □ Yes □ No Type: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duration: ________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency: ________________</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Range: __________________________

Duration: _______________________

Frequency: _____________________

**Application conditions:**

Access: ____________________________________________

____________________________________________________

Wind velocity: ________________________________

Temperature:   Substrate: ______ Environment:_______

Moisture:     Substrate:_______ Environment:________

Return to service time: ____________________________

Loading: _________________________________________

Vibrations:________________________________________

____________________________________________________

Fatigue: __________________________________________

____________________________________________________

Deflection:_______________________________________

____________________________________________________

**Geometric configuration of repair:**
Exposed surface area: ________________________________

________________________________

Surface orientation:
Horizontal: _____ Vertical: _______ Overhead: _______

Thickness of repair: ________________________________

________________________________

Size of exposed reinforcing bars: _________________

________________________________

Spacing of reinforcing bars: __________________________

________________________________

Clearance between reinforcing bars and substrate:_______

________________________________

Clearance between reinforcing bars: _________________

________________________________

Application method and placement properties:

Method: ________________________________

Properties: ________________________________

Flowability: ________________________________

Non-sag: ________________________________
Set time: _______________________________
2.0 Material Properties

Selecting repair materials that will perform satisfactorily under anticipated application and service conditions requires an understanding of how the new composite will respond to those conditions. For each condition, a response (effect) is generated. The response may occur at one or more locations within the repaired member: the surface, repair material, reinforcing steel, bond interface, or the substrate.

Example 1

**Condition:** Calcium chloride and moisture deposited on surface.

**Response:** As this cycle is repeated over time, chloride and moisture will penetrate through the concrete cover to the reinforcing steel. As threshold concentrations are reached, corrosion begins. Cracking allows easy ingress of water and chemicals and greatly accelerates the deterioration by providing a direct path to reinforcing steel as well as a site for concentration of salt deposits.

Example 2

**Condition:** Steel wheel travel over repaired joint nosing.

**Response:** Surface of repair is subjected to impact loading. This load will be distributed to the interface between the substrate and the new nosing material. If the load is not efficiently transmitted across the interface, failure of the repair material is likely.

Understanding the repair material’s response to each component of expected service conditions helps the user establish the specific material properties required to produce a durable repair.

To help the user identify required properties, the tables on the following pages provide examples of the structural, service, constructability, and appearance issues that should be addressed and resolved in the planning stage for most repair projects.
## Service Conditions: Structural Properties

<table>
<thead>
<tr>
<th>Performance Requirements</th>
<th>Undesirable Response (results if wrong material is selected)</th>
<th>Desirable Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond to substrate</td>
<td>Loss of bond, delamination; deterioration due to ingress of deleterious materials; lack of load transfer.</td>
<td>Tensile bond of repair system &gt; tensile strength of properly prepared substrate concrete</td>
</tr>
<tr>
<td>Load carrying as intended by the engineer</td>
<td>Does not carry loads as anticipated, overstressing either substrate or repair material. Load path remains in substrate concrete.</td>
<td>Modulus of elasticity similar to substrate</td>
</tr>
<tr>
<td></td>
<td>Carries loads initially, but over time, the repair relaxes under creep deformation. Load path transfers back to the substrate concrete.</td>
<td>Very low compressive creep</td>
</tr>
<tr>
<td></td>
<td>Drying shrinkage causes material to lose volume, reducing its ability to carry compressive loads. Load path transfers back to the substrate concrete</td>
<td>Very low drying shrinkage</td>
</tr>
</tbody>
</table>

**Note to Reviewers:**

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### Service Conditions: Exposure

<table>
<thead>
<tr>
<th>Repair Exposure Condition/Symptoms</th>
<th>Undesirable Response</th>
<th>Desirable Procedures / Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature changes</td>
<td>Cracking in repair material due to thermal contraction stresses</td>
<td>Thermal coefficient similar to that of substrate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spalling due to thermal expansion stresses in repair material or substrate (bond strength or substrate strength &lt; repair tensile strength)</td>
<td>Thermal coefficient similar to that of substrate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature changes within repair material at early ages</td>
<td>Deformation due to thermal expansion from high exotherm</td>
<td>Low exotherm during cure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deformation due to thermal contraction stresses in repair material</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rust staining, cracking adjacent to reinforcement, reinforcement section loss</td>
<td>Corrosion of reinforcing steel; Disintegration of cement matrix adjacent to reinforcement</td>
<td>Effective cover, low permeability, no cracks, corrosion mitigation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture conditions, saturation; freezing and thawing</td>
<td>Disintegration of cement matrix, surface scaling</td>
<td>Resistance to freezing and thawing</td>
</tr>
<tr>
<td>Moisture conditions</td>
<td>Cracking due to improper curing, plastic shrinkage, drying shrinkage</td>
<td>Proper curing, low plastic shrinkage, low drying shrinkage, low permeability</td>
</tr>
</tbody>
</table>

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## Service Conditions: Dynamic Loading

<table>
<thead>
<tr>
<th>Repair Exposure</th>
<th>Undesirable Response</th>
<th>Desirable Procedures / Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Condition/Symptoms</strong></td>
<td>(results if wrong material is selected)</td>
<td></td>
</tr>
<tr>
<td>High velocity water flow</td>
<td>Erosion by cavitation</td>
<td>High compressive strength; high tensile strength; small size aggregate; specialty coatings</td>
</tr>
<tr>
<td>Low velocity flow with waterborne debris</td>
<td>Erosion by abrasion</td>
<td>High abrasion resistance; high compressive strength; large size aggregate; specialty coatings</td>
</tr>
<tr>
<td>Vehicle wheels</td>
<td>Abrasion damage to surface</td>
<td>High compressive strength; high abrasion resistance; specialty toppings</td>
</tr>
<tr>
<td></td>
<td>Edge spalling at joints</td>
<td>High compressive, tensile, and bond strengths; high surface hardness for joint filler material (example, Shore A Hardness); tensile anchorage into substrate; armored joint edges</td>
</tr>
<tr>
<td>Impact</td>
<td>Spalling</td>
<td>High tensile and impact strengths; internal tensile reinforcement; high compressive strength</td>
</tr>
<tr>
<td>Fatigue Resistance</td>
<td>Cracking and crack propagation, loss of bond</td>
<td>Malleability; energy absorption; toughness</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------------------------------------</td>
<td>-----------------------------------------</td>
</tr>
</tbody>
</table>

Note to Reviewers:

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## Application Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Performance Requirements</th>
<th>Desirable Procedures / Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constructability</td>
<td>Quick turnaround time</td>
<td>Rapid strength gain</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Clock" /></td>
<td></td>
</tr>
<tr>
<td>Working time</td>
<td>Adequate for mixing and application method</td>
<td>Longer working time is better if return to service constraints can be met</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Consistency and rheology</td>
<td>As needed for application method and repair orientation</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Consistency" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trowel overhead</td>
<td>Non-sag</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Trowel" /></td>
<td></td>
</tr>
<tr>
<td>Material availability</td>
<td>Adequate shelf life, delivery schedule coincident with application usage</td>
<td>Ambient storage, convenient package size, local supply</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental considerations</td>
<td>Vibration, dust, noise, debris removal, hazardous material abatement</td>
<td>Shall satisfy governing regulatory requirements</td>
</tr>
<tr>
<td>Access</td>
<td>Allocated working time, equipment clearance, utility requirements, weight restrictions</td>
<td>Appropriate for repair application</td>
</tr>
</tbody>
</table>

## Owner Requirements

### Performance Requirements

<table>
<thead>
<tr>
<th><strong>Undesirable Response</strong> (results if wrong material is selected)</th>
<th><strong>Desirable Procedures / Properties</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Drying shrinkage cracks</td>
</tr>
<tr>
<td>Plastic shrinkage cracks, bleeding, settlement, absorption, evaporation</td>
<td>Low surface water loss during placement, stable mixtures, proper substrate and formwork conditioning</td>
</tr>
<tr>
<td>Installed cost</td>
<td>Change orders, overruns</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Return to use</th>
<th>Delays, penalties</th>
<th>Corresponds with forecast schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service life less than required</td>
<td>High maintenance and life-cycle cost</td>
<td>Low life-cycle cost, periodic inspection and preventative maintenance</td>
</tr>
<tr>
<td>Cleanability</td>
<td>Stains, contamination</td>
<td>Smooth, impervious surface, thermal shock resistant (steam cleaning)</td>
</tr>
<tr>
<td>Slip resistance</td>
<td>Liability, injury</td>
<td>Texture appropriate for traffic conditions</td>
</tr>
</tbody>
</table>

**Note to Reviewers:**
Please note that due to the editorial changes, the drawings on this page and previous two pages are not in their respective appropriate boxes/rows. The final editorial review of the document will be performed by the ICRI staff and that will take care of the formatting changes and put the figures in their appropriate boxes/rows.
3.0 Determining Properties

Repair materials should not be specified until the properties that will best satisfy overall project objectives are determined. These properties need to be identified and prioritized. The availability of a material providing all of the optimum values of the many properties under consideration is unlikely. Optimizing one property will most likely be achieved at the expense of other needed properties. For example, an increase in cement content to obtain high compressive strength will usually be accompanied by an increase in drying shrinkage.

The highest repair performance cannot be achieved unless competing demands have been prioritized, and those properties most critical to the success of the repair are identified to facilitate selection of an appropriate repair material and repair method.

Once the needs and performance criteria for the repair project are established (1.0 Project Objectives), a list of desirable properties is developed. Properties should be classified and organized as basic or special needs. Basic properties are those required to produce a fundamentally sound repair. Typically, these will be consistent through a broad range of repair applications.

Special properties are those which provide material performance to enhance durability within a specific load criteria. Since the relative importance of special properties is highly situational, the mix of properties selected may vary substantially from one application to the next. Once basic requirements have been identified, special property needs may be identified and ranked in descending order of importance. Properties which are not required should not be listed. Making compromises in basic properties to enhance special property performance risks repair failure. Two sample lists are shown on the following page.
Note: Although this section contains some references to polymer matrix materials, the emphasis throughout is on cement-based materials. “Polymer-modified” repair materials should not be confused with “polymer” repair materials and mortars. Typically, “polymer-modified” refers to the addition of a latex (powder or liquid) to an inorganic cement-based mortar. When cured, the resulting concrete contains a continuous, interconnected matrix of latex polymer particles. The Concrete Repair Terminology defines the following terms:

- **concrete, polymer**—a composite material in which the fine and coarse aggregates are bound together in a dense matrix with a polymer binder; also known as resin concrete.

- **concrete, polymer-modified**—a mixture of water, hydraulic cement, aggregate, and a monomer or polymer; polymerized in place when a monomer is used

Polymer concretes and repair mortars are generally thermosetting plastic materials, usually containing an aggregate filler. Materials such as epoxies, polyesters, vinyl esters and methyl-methacrylates are “polymers.”
# Examples of Prioritizing Property Needs

<table>
<thead>
<tr>
<th>Example 1: Partial column repair</th>
<th>Example 2: Slab resurfacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>The columns exhibit numerous spalls caused by carbonation and subsequent corrosion. The environmental temperature is fairly stable throughout the year. To assure adequate load distribution throughout the member, the repair composite must be able to carry a proportional amount of the compressive load.</td>
<td>Constant abrasion of wheel loads cuts depressions in the slab, causing the surface to become irregular. Exterior environment is subject to chlorides.</td>
</tr>
</tbody>
</table>

## Basic property needs

<table>
<thead>
<tr>
<th>Example 1</th>
<th>Example 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bond new to old</td>
<td>1. Bond new to old</td>
</tr>
<tr>
<td>2. Very low drying shrinkage</td>
<td>2. Very low drying shrinkage</td>
</tr>
</tbody>
</table>

## Special property needs

<table>
<thead>
<tr>
<th>Example 1</th>
<th>Example 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Modulus of elasticity similar to existing concrete</td>
<td>1. Similar coefficient of thermal expansion</td>
</tr>
<tr>
<td>2. Very low compressive creep</td>
<td>2. Sufficient abrasion resistance</td>
</tr>
<tr>
<td>3. Resistance to carbonation and moisture intrusion</td>
<td>3. Compressive strength to transfer wheel loads to underlying concrete substrate</td>
</tr>
<tr>
<td></td>
<td>4. Low permeability to reduce exposure of steel reinforcing to chlorides</td>
</tr>
</tbody>
</table>
3.1 Bond Strength

In most cases, good bond between the repair and the existing concrete substrate is a primary requirement for a successful repair. Bond failure between repair materials and an adequately prepared concrete substrate are not common and a properly prepared substrate will almost always provide sufficient bond strength. However material properties that can lead to bond failure are differential thermal strains and drying shrinkage.

Bond is best specified as a surface preparation requirement. The test methods described in the section “Bond Strength” of ACI 546.3R describe the various test methods in common use. Bond test values are most valid when used in conjunction with surface preparation, application techniques, and substrate of the actual or a similar repair. Systematic follow-up testing on completed repairs should generally be specified to verify compliance with engineering requirements. Of the test methods described, direct tensile test is the only method which can provide on-site strength data.

3.1.1 Bond Strength—Direct Tensile Test

Direct tensile testing (Fig. 3-1) measures the tensile bond or tensile strength of surface repairs and overlays. Tensile testing will expose the location of the weakest link in the composite system (repair material, interface, and substrate). Uniaxial testing equipment can be used to perform both field and laboratory tests. In-situ testing is performed by coring through the repair material into the substrate (Caution—In post-tensioned structures, proceed with extreme caution; Tendons should be located prior to conducting any coring operations). The coring procedures should be conducted in accordance with ICRI Technical Guideline No. 210.3R (formerly No. 03739), Guide for Using In-Situ Tensile Pulloff Tests to Evaluate Bond of Concrete Surface Materials, so as to not break off the core at the substrate. The drilling equipment should be in good condition and secured to avoid lateral movement and maintain proper alignment to the
coring surface, without unnecessary movement that could negatively impact the test sample. While the core remains connected to the substrate, a tensioning device is attached to the core and loaded until failure occurs. Tensile values are determined by dividing the load at failure by the cross-sectional area of the core.

**Test Methods:**

ASTM C1583, Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength of Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)

ICRI Technical Guideline No. 210.3R (formerly No. 03739), Guide for Using In-Situ Tensile Pulloff Tests to Evaluate Bond of Concrete Surface Materials

CAN/CSA-A23.2, Test Methods and Standard Practices for Concrete

**Minimum Requirement:** The required repair material to concrete substrate bond strength should be determined for each specific project based on a combination of structural strength requirements, long-term durability of the repair, and volume change compatibility. Experience demonstrates that bond strengths of 250 psi or greater can be achieved with readily available surface preparation and repair techniques in moderate-to good-quality concrete substrates. In addition, most concrete surface repair or overlay repair materials have a direct tensile strength (CRD C 164) in excess of 250 psi. Accordingly, concrete repair materials should have the potential to achieve a minimum repair material to concrete substrate bond strength of 250 psi, or at least the direct tensile strength of the repair material. Most repair material manufacturers report bond strength on their data sheets. This bond strength should be determined and reported as indicated in Section 5.12 of Guideline No. 320.3R-2012 – Guideline for Inorganic Repair Material Data Sheet Protocol.

In the field, the tensile bond strength may be limited by the in-situ tensile pull-off strength of the prepared concrete substrate. Therefore, the required pull-off strength criteria for a specific project should not exceed the in-situ tensile pull-off strength of the existing substrate or the direct tensile strength of the repair or
overlay material, whichever is lower. Field trials are recommended to evaluate the capacity of the existing concrete substrate and the repair material installation. If field trials demonstrate that the in-situ tensile pull-off strength of the existing concrete substrate or the repair material is inadequate, the advisability of making the repair should be re-evaluated. Further discussion on bond testing and acceptance criteria are discussed in ICRI 210.3R. If unexpected job conditions are encountered, including lower or higher strength of the existing concrete substrate to be repaired, acceptance criteria may have to be adjusted to meet specific project conditions.

Commentary: The direct tensile test (ICRI 210.3R and ASTM C1583) is an important quality assurance/quality control test. Both ICRI 210.3R and ASTM C1583 provide a description of the procedures and equipment needed for tensile testing. The test method provides a reasonable technique for evaluating materials, substrate, preparation, and placement procedures. Significant substrate or material weakness or deficiencies in preparation or placement can be detected with using this test.

3.1.2 Bond Strength—Direct Shear Test

Direct shear testing (Fig. 3-2) measures the shear strength of the bond between the repair material and the substrate. A special guillotine apparatus is used to subject core specimens to direct shear loads. Specimen cores for testing may be removed from the field or prepared in the laboratory. Shear bond values are determined by dividing the recorded load at failure by the bond area.

Test Method: Michigan DOT Shear Bond

Minimum Requirement: (see commentary)

Commentary: Values derived from this method are highly dependent upon substrate strength and surface preparation methods. For comparison purposes, differences between specimens having different substrate
strengths and surface preparation methods will render the testing data meaningless. The most useful testing of this type will be done with substrate materials removed from the structure to be repaired, and prepared exactly as they would be by field personnel. If shear bond values are specified as material requirements, they should be verified as described immediately above. If measurement of tensile bond in the repair composite is specified, it may be redundant to also specify direct shear bond requirements.

Refer to ACI 546.3R for discussion of additional methods of evaluating bond strength.

3.1.3 Bond Strength—Slant Shear Test

Bond strengths determined by slant-shear tests (Fig. 3-3) are most often reported by material suppliers. Bond values are determined by dividing the load at failure by the elliptical bond area.

**Test Methods:**

ASTM C882, Bond Strength of Epoxy-Resin Systems Used with Concrete**

ASTM C1042, Bond Strength of Latex Systems Used with Concrete

**Test Methods (continued):**

AASHTO T237, Testing Epoxy Resin Adhesive***

---

**Test methods cited in this manner are from the ASTM International Annual Book of ASTM Standards.

***Test methods cited in this manner are from the American Association of State Highway and Transportation Officials Standard Specifications for Transportation Materials and Methods of Sampling and Testing.

**Minimum Requirement:** (see commentary)

**Commentary:** Bond strengths determined by slant shear tests are highly dependent on the compressive strength of the substrate portion of the test cylinder. Therefore, slant shear bond strengths have little or no
value in comparing alternate materials—unless the tests were conducted with equal substrate strengths.

Results of screening tests reported by Best and McDonald (1990) indicated that for a constant substrate strength, slant shear bond strengths for both dry and wet surfaces are generally proportional to the compressive strength of the repair material. Subsequent tests on selected repair materials revealed poor correlation between bond strengths determined by slant-shear and direct tension test methods.

3.2 Dimensional Behavior

Relative dimensional changes between a surface repair material and an existing substrate can affect bond, ability to carry loads, durability, and appearance. Drying shrinkage, thermal coefficient, modulus of elasticity, and creep are all material properties which influence dimensional behavior. The U. S. Army Corps of Engineers initiated a research program to develop performance criteria for repair materials that are dimensionally compatible with existing concrete substrate. Their findings are summarized in the following four reports:

   
   [link](http://www.dtic.mil/dtic/tr/fulltext/u2/a295136.pdf)

   
   [link](http://acwc.sdp.sirsi.net/client/search/asset/1004727)

   
   [link](http://acwc.sdp.sirsi.net/client/search/asset/1004730)

3.2.1 Drying Shrinkage

It is extremely important to minimize drying shrinkage for cement-based materials. Experimental results and in-situ performance strongly suggest that volume changes in cement-based repair materials lead to many failures (Fig. 3-4). These include shrinkage cracking, delamination, loss of load-carrying capacity, corrosion of embedded reinforcing steel, and poor appearance (Fig. 3-5). One of the greatest challenges in the selection of repair materials is to achieve relative dimensional compatibility with the substrate. Though difficult, the selection of repair materials with minimal drying shrinkage is critical for durable repairs.

The identification and selection of low shrinkage materials requires an understanding of the drying shrinkage process. Repair materials are frequently mixed and placed with more water than needed for hydration. As the repair assumes the humidity of the surrounding environment, the material shrinks in volume, and tensile stresses accumulate in the repair material. Wet curing of cementitious materials will postpone the start of the drying process, and may cause slight expansion. As the repair material contracts, it resists cracking until the stress exceeds its tensile strength. The time required for a repair material to attain a stable drying shrinkage is dependent upon several variables including:

- Ambient temperature
- Wind speed
- Rate of hydration
- Mass or thickness of the material (larger mass or a greater thickness takes longer for the drying shrinkage process to complete)
• Permeability of the repair material (low permeability material takes longer for the drying shrinkage process to complete)

• Ambient relative humidity (the drying shrinkage process is faster in dry environments)

• Relative humidity of the substrate

The majority of ultimate drying shrinkage may occur within thirty days, or require as long as a year and longer to complete depending on ambient conditions, the geometry and depth of the repair, and the amount of moisture present in the repair material and substrate.

**Test Method:** ASTM C157, Length Change of Hardened Hydraulic Cement Mortar and Concrete, as modified in ICRI 320.3R. The use of smaller dimension specimens (i.e. 1x1x10” [25x25x250 mm]) will accelerate the shrinkage rate compared to larger dimension specimens (3x3x10” [75x75x250 mm] or 4x4x10” [100x100x250 mm]) due to a higher surface to volume ratio in the smaller specimens. Ultimate length change values (which can take up to a year) should be comparable between the different specimen sizes. Other drying shrinkage and volume change methods are discussed in the section “Volume Stability” of ACI 546.3R.

**Commentary:** A preferred repair material would have low drying shrinkage. Although repair materials with low drying shrinkage may crack after placement, high drying shrinkage materials carry a much higher probability of developing drying shrinkage cracks. Shrinkage values vary greatly between mixture proportions, manufacturers, and products. This fact was demonstrated by Gurjar and Carter (1987) in tests on forty-six repair materials. These test results have been sorted and categorized as shown in *Fig. 3-7 (previous page).* The magnitude of variation in these data is convincing evidence that careful investigation of actual shrinkage properties needs to precede the selection of suitable repair materials.
3.2.2 Coefficient of Thermal Expansion

All materials expand and contract with changes in temperature. For a given change in temperature, the amount of expansion or contraction depends on the coefficient of thermal expansion of the material (Fig. 3-8).

Test Methods:

Various test methods used for determination of the coefficient of thermal expansion are discussed in the section “Coefficient of thermal expansion” in ACI 546.3R. A recommended test method for cementitious materials is discussed in ICRI 320.3R.

Commentary: A large difference between the coefficient of thermal expansion of repair material and substrate could cause dimensional incompatibility in the two materials leading to system failure. Although the coefficient of thermal expansion of conventional concrete will vary somewhat, depending on the type of aggregate, it is usually assumed to be about 6 millionths per degree Fahrenheit \((6 \times 10^{-6}/\text{°F}; 10.9 \times 10^{-6}/\text{°C})\). Generally, cement-based repair materials will exhibit a coefficient of thermal expansion similar to that of concrete. However, the use of polymer-matrix based materials in repairs subject to wide variations in temperature will require careful consideration. According to ACI 503.5R, the coefficient of thermal expansion for unfilled polymers such as methyl methacrylates, epoxies, polyesters, polyurethanes, and styrene-butadiene is 4 to 18 times greater than that of concrete. The addition of fillers or aggregate to polymers will improve thermal compatibility—but the coefficient of expansion for the polymer-aggregate combinations will still be 1.5 to 5 times that of concrete. As a result, polymer repair materials will attempt to expand or contract more than the concrete substrate. This movement, when restrained through bond to the existing concrete, induces stress that can cause cracking and delamination as the repair material attempts to contract, or buckling and spalling as it expands. Thermal compatibility is especially important in large
repairs. To minimize expansion and contraction stress, polymer mortars and polymer concretes are typically recommended only in small volume repairs when used in exterior applications.

3.2.3 Modulus of Elasticity

Modulus of elasticity is a measure of stiffness. Higher modulus materials will deform less under a given load than will lower modulus materials (Fig. 3-9).

Test Methods:

Test methods for determination of the modulus of elasticity are described in ACI 546.3R.

Recommended Value: (see commentary)

Commentary: In general, the modulus of elasticity of a structural repair material should be similar to that of the concrete substrate or the effects of the differing modulus should be considered in the design of the repair. Compatibility between the modulus of elasticity for a structural repair material and concrete substrate helps to achieve a uniform load transfer across the repaired section. For non-structural applications, it is sometimes considered desirable to specify a repair material with a lower modulus of elasticity than that of the substrate to minimize the load likely to be transferred to the repair and thereby reducing the potential for cracking and delamination. In particular, a repair material with lower modulus of elasticity than that of the substrate may also be 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 (structural repair), it is desirable for the modulus of elasticity of both materials to match as closely as possible. Significant deviations in the modulus of elasticity of repair material and concrete substrate can lead to uneven load distribution and premature system failure. Additional discussion can be found in ACI Technical Note ACI 364.5T-10 Importance of Modulus of Elasticity in Surface Repair Materials.
3.2.4 Creep (Tensile and Compressive)

Creep is time-dependent deformation due to sustained load (Fig. 3-10). Tensile or compressive creep can be important if significant stress is induced in the repair material due to restraint of shrinkage strains or factors such as thermal movement or application of loads. For repairs that are not subjected to significant compressive forces, compressive creep may not be a significant property to consider. 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; Iriya et al. 2000; Beaudoin 1982).

Test Methods:

Test methods for determination of creep are discussed in ACI 546.3R.

Commentary: In structural repairs, creep of the repair materials generally should be similar to that of the concrete substrate. For (non-structural) protective repairs, however, higher creep is sometimes considered to be an advantage. In the latter case, strain relaxation through tensile creep may reduce the potential for cracking (Fig. 3-11).

Although creep of concrete in compression has been extensively investigated, information on tensile creep behavior is limited. The lack of published data is attributed to the fact that concrete is rarely subjected to direct tension. Also, there are significant experimental difficulties when a uniaxial load is required and strains have to be measured very accurately, especially in a material which is drying under load and where shrinkage is the predominant deformation.
It should be noted that polymer mortars and concrete exhibit widely differing creep behavior because the binders in polymer mortars are fundamentally different from the cement binder in concrete.

3.2.5 Restrained Shrinkage

The restraint of shrinkage which occurs when a repair material is bonded to a substrate will produce tensile stress in the repair material. Because concrete also creeps in response to sustained loads, a complex interaction between strength gain, shrinkage, modulus, creep, and other factors governs the cracking potential of the material.

Test Method: ASTM C1581, Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete Under Restrained Shrinkage. This test method also commonly known as the “Ring Test” is also described in the ACI 546.3R as well as ACI 364.3R reports.

Commentary: ASTM C1581 was adopted in 2004 and revised in 2009. Some guidance regarding the interpretation of results is provided in the appendix and references of the test method. ASTM suggests reporting the following information:

- Properties of the material being tested: mixture proportions, air content, slump/flow and density of concrete mixtures, and mixture proportions; flow; and density of mortar mixtures
- Type and duration of curing
- Daily ambient temperature and relative humidity data for the test environment
- Plots of steel ring strain versus specimen age for each test specimen
- Average age at cracking
- Age when the test was terminated for specimens that have not cracked during the test
- Average initial strain
- Average maximum strain
• Plots of net strain versus square root of elapsed time for each specimen

• Average stress rate at cracking or at the time the test was terminated

**Recommended Values**

In this test, longer time to cracking is preferred. ASTM C1581 provides guidance for classification of different materials based on the results of this test in the appendix to the test method. The table below lists this classification:

<table>
<thead>
<tr>
<th>Net Time-to-Cracking, ( t_{cr} ) days</th>
<th>Average Stress Rate, ( S ) (MPa/day)</th>
<th>Average Stress Rate, ( S ) (psi/day)</th>
<th>Potential for Cracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 &lt; ( t_{cr} ) ≤ 7</td>
<td>( S ≥ 0.34 )</td>
<td>( S ≥ 50 )</td>
<td>High</td>
</tr>
<tr>
<td>7 &lt; ( t_{cr} ) ≤ 14</td>
<td>( 0.17 ≤ S &lt; 0.34 )</td>
<td>( 25 ≤ S &lt; 50 )</td>
<td>Moderate-High</td>
</tr>
<tr>
<td>14 ( t_{cr} ) ≤ 28</td>
<td>( 0.10 ≤ S &lt; 0.17 )</td>
<td>( 15 ≤ S &lt; 25 )</td>
<td>Moderate-Low</td>
</tr>
<tr>
<td>( t_{cr} &gt; 28 )</td>
<td>( S &lt; 0.10 )</td>
<td>( S &lt; 15 )</td>
<td>Low</td>
</tr>
</tbody>
</table>

The net time-to-cracking for the material is the difference between the age at cracking and the age drying was initiated. If a test material cracks during the period of curing (that is, before drying is initiated), the net time-to-cracking is zero. A classification table shown above for cracking potential based on the net time-to-cracking and the average stress rate at cracking or at the time the test is terminated is provided to aid in the comparison of materials. The net time-to-cracking classification in Table X1.1 can be used to assess the relative performance of materials that crack during the test. For materials with average stress rates lower than 0.10 MPa/day [15 psi/day] that have not cracked during the test, the magnitudes of average stress rate can be compared to assess the relative potential for cracking. This allows for an appropriate comparison of materials where time constraint does not permit testing to be carried out until cracking occurs.

**3.3 Durability Properties**

Durability of concrete is defined as its ability to resist weathering action, chemical attack, abrasion, and any other conditions of service. If a repair becomes necessary because of deterioration of the existing concrete, it is essential to establish the cause and extent of deterioration. Based on this information, a repair strategy can...
be selected which will provide a durable repair. A durable repair will retain its original form, quality, and serviceability when exposed to its environment. Material properties that can affect the durability of a repair are discussed in the following paragraphs.

3.3.1 Permeability

Permeability is defined as the property that governs the rate of flow of a fluid (liquid or gas) into a porous solid (Mehta and Monteiro 1993). This property is a useful indicator of the corrosion protection which a material may provide. Soluble chlorides which can lead to chloride-induced corrosion are typically carried in solution through the pore structure from the surface to the steel reinforcing. Low permeability will reduce the rate at which chlorides penetrate the protective cover.

Similarly, low permeability will reduce the rate at which atmospheric or dissolved CO$_2$ diffuses through the pore structure of the concrete cover. This process, known as carbonation, lowers material pH, and depending on the depth of carbonation, depth of steel reinforcement, and availability of moisture and oxygen, may lead to corrosion of steel reinforcement.

Test Methods:

AASHTO T259, Resistance of Concrete to Chloride Ion Penetration

AASHTO T277, Rapid Determination of the Chloride Permeability of Concrete

ASTM C1202, Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration

ASTM C1543, Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding

The test data produced by AASHTO T277 and ASTM C1202 are generally known as “rapid chlorides.” The title of the ASTM C1202 method, “Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration,”
Penetration,” is a more accurate statement of the property being assessed. These tests do not directly measure permeability of the material.

**Commentary:** There are many repair strategies which can be employed to delay the damaging effects of aggressive chemicals such as chlorides. A common approach is to select and install low permeability repair materials (including overlays) that will resist chloride penetration. Other methods include the use of crack injection, crack and joint sealants, surface sealers, coatings and membranes. The common practice of using rapid chloride data to specify allowable permeability is controversial. (Pfeifer, McDonald, and Krauss 1994). The presence of some inorganic admixtures and free ions such as chloride ions in the concrete can result in the passage of electrical charge (coulombs) indicating a higher apparent permeability. Data generated by AASHTO T259 are considered to be a more reliable indicator of material permeability. Rapid chloride data alone should not be used for purposes of comparison unless the correlation for the specific material type has been established using the long-term chloride ponding procedure described in AASHTO T259.

### 3.3.2 Water Vapor Transmission

Water vapor transmission rate is defined by ASTM as the steady water vapor flow in a unit of time through a unit area of a body, normal to specific parallel surfaces, under specific conditions of temperature and humidity at each surface.

**Test Method:** ASTM E96, Water Vapor Transmission of Materials (*Fig. 3-12*).

**Commentary:** If impermeable materials are used for large repairs, water vapor transmitted through the concrete substrate can be trapped at the interface between the repair and the substrate. This entrapped water can be a particularly troublesome problem in relatively thin repairs subject to cycles of freezing and thawing. The hydraulic pressure caused by freezing of the entrapped moisture may result in debonding of...
the repair, or the substrate will become critically saturated and, if the concrete does not contain properly
entrained air, the substrate will likely suffer freeze-thaw deterioration. Shotcrete repairs to a navigation lock
wall illustrate this problem (HQUSACE 1995). The generally good resistance of shotcrete to cycles of
freezing and thawing (despite a lack of entrained air) is attributed in part to its low permeability, which
minimizes the ingress of moisture, thus preventing the shotcrete from becoming critically saturated. When
moisture migrates through the substrate, however, the shotcrete is unable to efficiently transmit this
moisture to the exposed surface, and the existing concrete becomes saturated. Subsequent cycles of freezing
and thawing will result in failure of the repair (Fig. 3-13). Cores through the repair show the remaining
shotcrete to be in generally good condition; however, the original concrete immediately behind the shotcrete
exhibits significant deterioration (Fig. 3-14). Cores of similar concrete from portions of the wall which did
not receive a shotcrete overlay were in generally good condition from the surface inward.

3.3.3 Resistance to Freezing and Thawing

The causes of deterioration from freezing and thawing are complex and are not exclusively derived from the
expansive pressure generated by water in its frozen state. It is, however, sufficient to define freezing and
thawing deterioration as failure in the cement matrix or in porous aggregate particles which occurs when the
material is frozen while critically saturated. A material that has demonstrated resistance to freezing and
thawing in laboratory tests or previous field applications should be specified for repairs that will be
subjected to this service condition.

Test Method: ASTM C666, Resistance of Concrete to Rapid Freezing and Thawing

Procedure A: rapid freezing and thawing in water (most common method).

Procedure B: rapid freezing in air and thawing in water.

Recommended Value: (see commentary)
The test is designed to run 300 cycles or until the relative dynamic modulus reaches 60% of original value. Data from a reduced number of cycles may not be used for comparative purposes—unless the procedure was terminated by dynamic modulus limitations.

**Commentary:** The normal test for evaluating freeze-thaw resistance, ASTM C666, exposes specimens to freezing at an intermediate level of maturity with no opportunity for drying prior to testing and exposes them to a very rapid freezing cycle. There are many examples of repair materials, among them certain latex-modified formulations that perform well in field applications but cannot yield a high durability factor when tested in accordance with C666. Although the test is excellent for assessing the resistance to freezing and thawing of young saturated specimens to severe exposure, the resistance of mature specimens to more typical exposures might be better assessed by altering the age-at-test and specimen-conditioning requirements of C666 to more accurately reflect actual service conditions, or by replacing it with a critical dilation test such as ASTM C671, Critical Dilation of Concrete Specimens Subjected to Freezing. (For further information, see ACI 201.2R.)

### 3.3.4 Resistance to Scaling

Scaling is defined as the flaking or peeling away of the near-surface portion of hardened concrete or mortar. This loss of cement mortar from the finished surface can be caused by hydraulic and osmotic pressures caused by freezing. Scaling is frequently initiated by the application of deicing chemicals in below-freezing conditions. Moderate to severe scaling deterioration will expose coarse aggregate. Scaling resistance should be considered whenever the repair material will be subjected to deicing chemicals.

**Test Method:** ASTM C672, Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals (Modified)

Modification: collect and weigh scaled material after every fifth cycle in lieu of the visual rating system.
**Recommended Values:** &lt;0.10 lb/ft$^2$ (0.5 kg/m$^2$) loss at 50 cycles (*Fig. 3-15*).

**Commentary:** ASTM C672 is widely accepted as a good indication of resistance to scaling from deicing chemicals. The modification noted above provides for a more objective rating of individual materials. A repair material with a scaling resistance classified as good or very good is appropriate for applications exposed to freezing and thawing cycles.

### 3.3.5 Sulfate Resistance

Sulfate attack causes the chemical decomposition of certain binder compounds in hydrated cement paste (*Fig. 3-16*). Decay of organic matter in marshes and shallow lakes is a primary source of naturally occurring sulfates. Soils in regions long ago covered by inland seas frequently contain enough water-soluble sulfates to precipitate sulfate attack. Other sources of sulfate include chemical process effluent, agricultural runoff, and wastewater treatment. Sulfate resistance must be considered for the repair of structures exposed to these environments, such as piers, dams, bridge columns, buried concrete pipe, wastewater treatment facilities, transmission tower footings, and highway pavements.

**Test Method:** ASTM C1012, Length Change of Hydraulic-Cement Mortars Exposed to Sulfate Solutions.

**Recommended Value:** The ASTM subcommittee which developed C1012 recommended adoption of the following performance criteria:

- **Moderate Sulfate Resistance:** 0.10% maximum expansion at 6 months
- **High Sulfate Resistance:** 0.05% maximum expansion at 6 months

**Commentary:** This test is considered to be a reliable indicator of the resistance of cement-based materials to sulfate attack (*Figure 3.17*). The test method is suitable for use on Portland-cement mortars, mortar blends containing pozzolans or slags, and polymer-modified mortars.
3.3.6 Alkali-Aggregate Reaction

Alkali-aggregate reaction is a chemical reaction in either mortar or concrete between alkalis (sodium or potassium) from cementitious materials or other sources, and certain constituents of some aggregates. There are two general types of alkali-aggregate reaction: alkali-silica reaction and alkali-carbonate reaction. Products of either reaction may cause abnormal expansion and cracking of mortar or concrete in service (Fig. 3-18). Expansion and cracking may develop within a few weeks or may not appear for a number of years after the mortar or concrete is placed.

Test Methods:

ASTM C227, Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
ASTM C289, Potential Reactivity of Aggregates (Chemical Method)
ASTM C295, Petrographic Examination of Aggregates for Concrete

Recommended Values: Criteria for evaluating the potential alkali reactivity of aggregates is discussed in ACI 201.2R and Appendices D and E of EM 1110-2-2000 (HQUSACE 1994).

Commentary: When the section thickness of repairs exceeds 1 to 2 in. (25 to 50 mm), manufacturers typically recommend the addition of coarse aggregate to repair mortars. The addition of aggregate improves dimensional stability, reduces exothermic heat, and generally results in a more economical repair. Although aggregate selection is systematically considered in original concrete construction, it is routinely overlooked for repair materials. This oversight can be costly because repair materials are likely to contain not only relatively higher levels of high-alkalinity cement, but a complex mixture of chemical and mineral admixtures as well.
When available, the field performance record of a particular aggregate, if it has been used with cement of high-alkali content, can be used to judge its reactivity. Laboratory tests should be made on aggregates from new sources, and when service records indicate that reactivity may be possible.

3.3.7 Abrasion Resistance

Abrasion resistance is defined as the ability of a surface to resist being worn away by rubbing and friction. Factors that influence the abrasion resistance of a repair material include amount and quality of aggregate, compressive strength, mixture proportions, type of material, finishing procedures, curing, and surface treatment.

Test Methods: The following test methods provide a variety of procedures for determining the relative resistance of repair materials to abrasion. The test methods are not intended to provide a quantitative measurement of the length of service that may be expected from a specific material.

ASTM C418, Abrasion Resistance of Concrete by Sandblasting, covers the laboratory evaluation of the relative resistance of concrete surfaces to abrasion by sandblasting. The procedure produces a cutting action which tends to more severely abrade the less resistant components of the concrete (repair material).

ASTM C779, Abrasion Resistance of Horizontal Concrete Surfaces, provides three procedures (revolving disks, dressing wheels, and ball bearings) for determining the relative abrasion resistance of horizontal concrete surfaces. The procedures differ in the type and degree of abrasive force they impart and are intended for use in determining variations in surface properties of cement-based materials.

ASTM C944, Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating Cutter Method. The primary application of this method is to evaluate the abrasion resistance of 6-in. (150-mm) core samples which do not have sufficient surface area to permit testing in accordance with ASTM C418 or C779.
ASTM C1138, Abrasion Resistance of Concrete (Underwater Method), covers a procedure for determining the relative resistance of concrete (including concrete overlays and impregnated concrete) to abrasion underwater. This procedure simulates the abrasive action of water-borne particles (silt, sand, gravel, and other solids).

Commentary: For material performance comparisons, the test data being evaluated must be generated by the same method. It is worth noting that the replication of these tests is relatively poor. With coefficients of variation ranging from 6 to 21% for single operator/same machine results, moderate differences in performance may not be reliably detected. Of the four methods, C779-A (revolving disks) has the highest precision.

3.4 Mechanical Properties

Repair materials require mechanical properties to carry and transfer loads similar to the concrete which is being repaired. In addition to externally applied loads, repair materials must also absorb and resist stress caused by restrained volume changes, including drying shrinkage and thermal expansion or contraction.

3.4.1 Tensile Strength

Tensile strength is an indication of a material’s ability to withstand tensile stress. Higher tensile strength can generally be expected to improve the resistance of a repair material to internal tensile stresses such as those due to restrained volume changes. While there are a number of ways to measure tensile strength, two of the more common methods follow. Direct tensile pull-off bond strength (Section 3.1.1, ASTM C1583) should not be confused with splitting tensile strength (ASTM C496) or direct tensile loading of a briquette (ASTM C190). While all three of these tests have the ability to evaluate tensile properties of the material, the values produced by these three tests are different and should not be taken as comparative to each other.

Test Methods: (Fig. 3-19)
Commentary: In many situations, repair materials are required to carry and transfer tensile loads. The tensile strength of a cement-based material is often estimated to be approximately 10% of its compressive strength. However, the tensile strengths of repair materials can vary significantly and are not necessarily predictable from compressive strengths.

Tensile strength measured using the C190 method is determined by a direct tensile loading of a briquette specimen. The small size of the briquettes—cross section of 1 square inch (650 mm²)—make it difficult to use with materials containing aggregate. Even though ASTM discontinued C190 in 1991, the procedure is still used for lack of an alternate direct tensile test.

The splitting tensile strength is a compressive test of a horizontal cylinder across its diameter. While not a direct tensile test, it is simpler to run and can be used to test materials containing aggregate or cores taken from the field. Either procedure can provide an indication of the tensile strength of a material. However, the results of the two tests are different. The splitting tensile strength (C496) produces a somewhat larger number than the direct tensile strength (C190).

The rate of tensile strength gain is also important and can be assessed by examining the tensile strength of a material at various ages, including some early age results (that is, 3 or 7 days). In general, the rate at which a material develops tensile strength must be rapid enough to exceed the induced tensile stress such as from drying shrinkage.
3.4.2 Flexural Strength

Flexural strength is a measure of a repair material’s resistance to bending. When repairs are likely to be subjected to bending, specifying flexural strength should be considered. While there are a number of test procedures for measuring flexural strength, two of the more common methods are listed below.

**Test Methods:** *(Fig. 3-20)*

- ASTM C78, Flexural Strength of Concrete Using Simple Beam with Third-Point Loading
- ASTM C348, Flexural Strength of Hydraulic Cement Mortars
- ASTM C42, Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

**Commentary:** ASTM C78 and ASTM C348 apply a load to the center of a stationary beam in order to determine the flexural strength. The differences are in the loading points and the size of the beam. C78 uses a third point loading (four contact points), and the reported result is a modulus of rupture in psi. C348 uses a 1-1/2 x 1-1/2 x 6½ in. (40 x 40 x 160 mm) beam while C78 uses a larger beam where the cross section is square and the length is three times the width of the beam—typical 6 to 8 in. (150 to 200 mm) in width and 18 to 24 in. (450 to 600 mm) in length. Test results using the third-point loading in C78 to determine modulus of rupture are usually higher than the flexural strengths determined using C348. For purposes of comparison, the results from these methods cannot be used interchangeably. The exclusive use of C348 for mortar specimens and C78 for concrete specimens is recommended.

3.4.3 Compressive Strength

The compressive strength of a repair material is a basic measure of its ability to carry compressive loads.

**Test Methods:**

- ASTM C109, Compressive Strength of Hydraulic Cement Mortars
ASTM C39, Compressive Strength of Cylindrical Concrete Specimens

(The two test methods above do not directly correlate, but can be compared using the equation: C109 result x 0.85 = C39 result.)

ASTM C42, Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

**Commentary:** For many applications, compressive strengths of repair materials should approximate the substrate strength. Differences in compressive strengths usually indicate differences in modulus of elasticity as well (see commentary under modulus of elasticity). Differences between repair material and substrate in these properties will generally affect strains and load transfer between the two materials. High compressive strengths are frequently achieved by increasing the cement content in the mixture design. Possible negative effects of higher cement content include increased drying shrinkage and increased temperature rise. In the specification process, the relative importance of this property needs to be carefully weighed against other desirable durability properties. High compressive strengths may, in some instances, adversely affect other properties needed to achieve a durable repair.

### 3.5 Constructability Properties

Constructability properties are properties of materials during early age and include plastic properties, initial set, and curing requirements. Some properties are designed to facilitate placement, but may adversely affect other material properties.

Surface repair material selection must consider the physical properties (e.g. shrinkage, bond strength, modulus of elasticity) needed to produce a repair composite capable of fulfilling its intended function. However, obtaining the desired results from the installed product can be difficult if constructability issues are not identified or properly communicated.
For example, field conditions such as a combination of high wind and low humidity can adversely affect a material’s shrinkage. Ambient, substrate surface, and material temperatures can influence setting characteristics and strength gain relationships. Field changes in the water-to-cement or polymer-to-cement ratios can affect many of the critical properties of the material. Incorrect mixing, placement, finishing, and curing can also alter the installed material’s properties. Knowing how field conditions may affect the material is an important step in the selection process.

An understanding of the physical and chemical properties of a material in its plastic state should influence the selection of the method of placement. Trowelable products, for example, have significantly different consistencies than those repair materials which are to be pumped. In turn, the selection process for a repair material to be placed in a small void at a twelfth floor spandrel beam will differ greatly from that which will be needed for a balcony slab replacement at the first floor level. Constructability is also influenced by the owner’s operating requirements. These requirements may include limited work space, no tenant interference, night work only, short duration, no noise, no odors, no dust, etc.

In addition to selecting a surface repair material based on physical performance criteria, the constraints of the field conditions should be evaluated. Detailed application instructions will minimize the risk of altering the physical properties of the installed material.

3.5.1 Flow Characteristics

Commentary: Repair material flow characteristics provide important properties which allow repair materials to penetrate and consolidate into repair cavities. With certain placement techniques, including form and pump, form and cast-in-place, or grouted pre-placed aggregate, flow characteristics are critical aspects for successful repair. For most of these applications, slump (or, slump flow or spread in the case of self-consolidating concrete (SCC)) requirements are satisfactory for specifying flowability. In grouted
preplaced aggregate applications, performance specifications require flowability to be measured with a flow cone (ASTM C939, Flow of Grout for Preplaced-Aggregate Concrete). High slump does not guarantee that the material will pump through a pump line and into a confined cavity. Pumpability is influenced by aggregate shape, gradation, and content of fines; size of pump line; pump line length; and type of pump.

Enhancing flow characteristics may adversely affect other critical properties, including material segregation, shrinkage, strength and permeability. The flow properties of materials are also a function of the mixing shear and time. ICRI Technical Guideline No. 320.5R, Pictorial Atlas of Concrete Repair Equipment, can be used as a means of specifying mixing equipment.

3.5.2 Rate of Strength Gain

Commentary: Rapid strength gain, as measured by compressive strength, is important to minimize shutdown time in many repair environments such as traffic areas. Insufficient strength gain prior to use may result in damage to the repair material or bond line. The desired strength and time duration should be specified where required. The rate of strength gain is highly dependent upon the temperature of cure. Higher temperatures will result in faster strength gain; lower temperatures will result in slower strength gain. Accurate measurement of in situ strength is best accomplished by match-curing specimens at temperatures similar to those which exist in the in situ repair material.

3.5.3 Exothermic Temperature Changes

Commentary: When water is added to cement, the reaction is exothermic, and a considerable amount of heat can be generated over an extended period of time. The heat liberated up to a specific time or age is measured in calories per unit weight of cement (cal/g). High-early strength cements are finer than other types of cement and sometimes contain other active chemical compounds, thereby producing higher earlier strengths and a more rapid release of heat. In thick section repair applications, failure to recognize the heat
factor and to provide for its dissipation will often result in thermal cracking. Thermal cracks are caused principally by the tensile stress created by steep temperature gradients that can develop between the interior and surfaces of curing concrete, as well as by the restraint of volume changes which occur as the material cools. While several design and construction practices are available to minimize thermal stresses, restricting the amount of heat generated is a fundamentally sound approach for mitigating thermal cracking. When positive control over temperature rise is desired, upper limits on the heat of hydration of the cement may be imposed through ASTM C150, Specification for Portland Cement; ASTM C595, Specification for Blended Hydraulic Cements; ASTM C1157, Standard Performance Specification for Hydraulic Cement; and ASTM C1600, Standard Specification for Rapid Hardening Hydraulic Cements.

3.5.4 Hot and Cold Weather Applications

Hot weather is defined as any combination of high temperature, low relative humidity, and wind velocity that impairs the quality of fresh or hardened repair material or otherwise results in abnormal properties. The effects of hot weather are most critical during periods of rising temperature, falling relative humidity or both. Precautionary measures required on a calm, damp/humid, overcast day will be less strict than those required on a dry, sunny, windy day, even if the air temperature is identical.

Adverse effects of hot weather include plastic shrinkage cracking, drying shrinkage cracking (from high water demand), poor or no bond, and poor surface finishes due to rapid setting (Fig. 3-21).

Cold weather is defined as a period when, for more than three consecutive days, the average daily temperature is less than 50°F (10°C) and the air temperature never rises above 55°F (13 °C) for more than 12 hours in any 24-hour period. Cold weather’s adverse effects include retarded strength gain, freezing of repair material and subsequent deterioration, and poor bond between the substrate and the repair material.
The specifier must ensure that the materials selected are appropriate for the conditions of application. ACI 305.1, Hot Weather Concreting and ACI 306.1R, Cold Weather Concreting specifications provide excellent information, and can aid in making repairs with materials not specifically manufactured for use in climatic extremes.

3.5.5 Working Time

Commentary: Working time is the amount of time available after a material is mixed until the material begins to set. Working time may become critically shortened and interfere with proper placement techniques at higher temperatures, especially for rapid setting materials. Working time is generally measured as number of minutes at a given temperature.

3.5.6 Compatibility with Surface Treatments

Commentary: In many repair situations, surface repair materials are used in conjunction with surface-applied coatings, linings, membranes, or sealers. Many delamination failures of surface-applied treatments have occurred in which the separation from the repair material was caused by some type of material or application incompatibility. Form release agents and curing compounds should be evaluated as materials that may affect adhesion or penetration of other surface treatments.

The specifier should identify those materials which pose a compatibility risk and determine whether these materials can be used together. This may be done by pilot/mockup testing, by previous experience, or by consulting the appropriate material manufacturers.

3.5.7 Compatibility with Substrate
Commentary: Some repair materials may generate adverse chemical reactions when exposed to certain substrate conditions. The specifier should question the product manufacturer to determine if the material being evaluated has the potential to react with the substrate being repaired.

3.6 Summary

Profiles of desired material properties or performance criteria for typical repair applications can be found in the following documents:

i. ICRI 320.3R, Guideline for Inorganic Repair Material Data Sheet Protocol.


   http://acwc.sdp.sirsi.net/client/search/asset/1004732

These guidelines can aid the user to matching requirements with the typical characteristics of selected materials.

4.0 Selecting Repair Materials

Most repair projects will have unique conditions and special requirements that must be thoroughly examined before the final repair material criteria can be determined. Once the criteria for a durable repair have been established, materials with the properties necessary to meet these criteria should be identified. A variety of repair materials have been formulated to provide a wide range of properties. Since these properties will
affect the performance of a repair, selecting the correct material for a specific application requires careful study.

Material Properties

Properties of the materials under consideration for a given repair may be obtained from the following:

1. Manufacturer’s data sheets
2. Evaluation reports
3. Contact with suppliers
4. Tests results

Manufacturer’s data for properties such as compressive strength, flexural strength, tensile strength, and slant-shear bond are frequently reported in material data sheets provided by suppliers. However, other material properties of equal or greater importance, such as drying shrinkage, modulus of elasticity, tensile bond strength, creep, permeability, and water vapor transmission, may not be reported. Experience indicates that the material properties reported in manufacturer’s data sheets are generally accurate for the conditions under which they were determined. However, the designer should beware of those situations in which data on pertinent material properties are not reported; unfavorable material characteristics are seldom reported.

Material properties pertinent to a given repair should be requested from manufacturers if they are not included in the data sheets provided. General descriptions of materials, such as “compatible,” “non-shrink,” etc. should be disregarded unless the claims are supported by data determined in accordance with standardized test methods. Material properties determined in accordance with “modified” standard tests should be viewed with caution, particularly if the modifications are not described.
The repair material manufacturer should demonstrate performance using consensus-based test methods developed by a national standards body whenever possible. In cases where these test methods are modified or not standardized, the modifications or non-standardized methods should be sufficiently documented in writing so that the published values may be verified by outside parties if so required when reproducibility is considered. Testing, whether performed by the material manufacturer or independently in accordance with written material manufacturer’s instructions should use test methods sufficiently documented to allow replication of the tests with consideration of the reproducibility of the test.

Acceptable proprietary repair material(s) other than site mixed portland-cement mortar may alternatively be used for repair. Repair materials include, but are not limited to, commercial repair material(s) products, including: latex modified cement mortar conforming to Type II in ASTM C1059, Latex Agents for Bonding Fresh to Hardened Concrete; epoxy mortars and epoxy compounds conforming to ASTM C881/C 881M, Epoxy-Resin-Base Bonding Systems for Concrete; packaged, rapid hardening concrete repair materials conforming to ASTM C928, Packaged, Dry, Rapid-hardening Cementitious Materials for Concrete Repairs; packaged, mortar and concrete conforming to ASTM C387, Packaged, Dry, Combined Materials for Concrete and High Strength Mortar; rapid hardening cement conforming to ASTM C1600, Rapid Hardening Hydraulic Cement; shotcrete conforming to ASTM C1436, Materials for Shotcrete and C1480/1480M, Packaged, Pre-Blended, Dry, Combined Materials for Use in Wet or Dry Shotcrete. Use repair material(s) in accordance with the repair material manufacturer’s recommendations. The repair material manufacturer’s written instructions should be followed unless not accepted by the Architect/Engineer. If the repair material manufacturer’s written instructions are modified, these modifications should be submitted to the Architect/Engineer for review and acceptance.
Results of tests on a variety of repair materials are available from several government agencies and independent testing laboratories. For example, the REMR Notebook (USAEWES 1985) currently contains 133 Material Data Sheets that include material descriptions, uses and limitations, available specifications, manufacturer’s test results, and Corps test results.

Reputable material suppliers can assist in identifying those materials and associated properties that have proven successful in previous repairs, provided they are made aware of the conditions under which the materials will be applied and the anticipated service conditions.

The formulations for commercially available materials are subject to frequent modifications for a number of reasons, including changes in ownership, changes in raw materials, environmental regulations, and new technology. Sometimes these modifications result in changes in material properties without corresponding changes to the manufacturer’s data sheets or notification of the modified formulation by the material supplier. Consequently, testing of the repair material is recommended if achieving certain specific material properties is considered critical to the viability or durability of the repair.

**Selection Considerations**

It is likely that more than one type of material will satisfy the design criteria for durable repair of a specific structure. However, it is necessary to consider other important factors such as ease of application, cost, and available labor skills and equipment in selection of the repair material. To match the properties of the concrete substrate as closely as possible, Portland-cement concrete or similar cementitious materials are frequently the best choices for repair. There can be exceptions, however, such as for repairs that must be resistant to chemical attack where use of protective coatings would be impractical. Finally, it should be understood that repairing “like with like” will not necessarily achieve a completely compatible repair since certain properties are time-dependent and the existing substrate has often been in place for many years.
Typical characteristics of some common repair materials are provided in the table below.
### Typical Characteristics of Some Common Repair Materials (see ACI 546.3R for further information)

<table>
<thead>
<tr>
<th>Material</th>
<th>Ingredients</th>
<th>Typical material admixtures</th>
<th>Application requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Binder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>portland cement mortar</td>
<td>portland cement</td>
<td>water reducing air-entraining</td>
<td>0.5 to 2.0 in. (13 to 50 mm)</td>
</tr>
<tr>
<td></td>
<td>cement</td>
<td></td>
<td>40 to 90°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>portland cement concrete</td>
<td>portland cement</td>
<td>water reducing air-entraining</td>
<td>&gt;1.75 in. (&gt;44 mm)</td>
</tr>
<tr>
<td></td>
<td>cement</td>
<td></td>
<td>40 to 90°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>microsilica-modified</td>
<td>portland cement</td>
<td>silica fume, HRWR²,</td>
<td>&gt;1.25 in. (&gt;30 mm)</td>
</tr>
<tr>
<td>portland cement concrete</td>
<td>cement</td>
<td>air-entraining</td>
<td>40 to 90°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>polymer-modified</td>
<td>portland cement</td>
<td>polymer latex</td>
<td>&gt;1.25 in. (&gt;30 mm)</td>
</tr>
<tr>
<td>portland cement concrete</td>
<td>cement</td>
<td></td>
<td>45 to 95°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 days</td>
</tr>
<tr>
<td>polymer-modified</td>
<td>portland cement</td>
<td>non-sag fillers, polymer</td>
<td>0.25 to 2.0 in. (6 to 50 mm)</td>
</tr>
<tr>
<td>polymer-modified</td>
<td>cement</td>
<td>latex or powder</td>
<td>45 to 95°F</td>
</tr>
<tr>
<td>polymer-modified</td>
<td>mortar</td>
<td>—</td>
<td>45 to 95°F</td>
</tr>
<tr>
<td>magnesium</td>
<td>magnesium</td>
<td>—</td>
<td>&gt;0.5 in.</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Material Type</th>
<th>Cement Type</th>
<th>Additives/Admixtures</th>
<th>Diameter/mm</th>
<th>Temperature/F</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>phosphate cement</td>
<td>phosphate cement</td>
<td>(&gt;19 mm)</td>
<td>(-18 to 40°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>preplaced aggregate</td>
<td>portland cement</td>
<td>pozzolans, fluidifier</td>
<td>&gt;3.0 in.</td>
<td>40 to 90°F</td>
<td>wet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt;76 mm)</td>
<td>(5 to 32°C)</td>
<td>7 days</td>
</tr>
<tr>
<td>epoxy mortar</td>
<td>epoxy resin</td>
<td>sand</td>
<td>0.13 to 0.50 in.</td>
<td>50 to 90°F</td>
<td>air</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(4 to 13 mm)</td>
<td>(10 to 32°C)</td>
<td></td>
</tr>
<tr>
<td>methyl methacrylate (MMA)</td>
<td>acrylic resin</td>
<td>sand</td>
<td>0.25 to 0.5 in.</td>
<td>20 to 120°F</td>
<td>air</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(6 to 13 mm)</td>
<td>[-6] to 50°C</td>
<td></td>
</tr>
<tr>
<td>shotcrete</td>
<td>portland cement</td>
<td>silica fume, pozzolans, water reducing admixture, accelerator, latex</td>
<td>&gt;0.5 in.</td>
<td>40 to 90°F</td>
<td>wet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt;13 mm)</td>
<td>(5 to 32°C)</td>
<td>7 days</td>
</tr>
</tbody>
</table>

1. The materials shown in this column are examples of additives/admixtures which may be used to adjust properties in cement-based materials.

2. High range water reducer

3. Portland cement mortars that are durable in application thicknesses of less than 1.5 in. (38 mm) are generally prepackaged, proprietary formulations.
Note: the material properties shown in this table vary between products and from manufacturer to manufacturer and are shown for comparison purposes only. See ACI 546.3R Table 2.1 and 2.2.

<table>
<thead>
<tr>
<th>Drying shrinkage</th>
<th>Coefficient of thermal expansion</th>
<th>Compressive strength</th>
<th>Elastic modulus</th>
<th>Permeability (% of concrete)</th>
<th>Freeze-thaw resistance</th>
<th>Non-sag quality</th>
<th>Exotherm</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>moderate</td>
<td>similar to substrate 0</td>
<td>650 psi (5 MPa)</td>
<td>2500 psi (20 MPa)</td>
<td>5000 psi (35 MPa)</td>
<td>3.4 x 10^6 psi (2.3 x 10^4 MPa)</td>
<td>good</td>
<td>moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>low</td>
<td>similar to substrate 0</td>
<td>650 psi (5 MPa)</td>
<td>2500 psi (20 MPa)</td>
<td>5000 psi (35 MPa)</td>
<td>3.8 x 10^6 psi (2.6 x 10^4 MPa)</td>
<td>good</td>
<td>N/A</td>
<td>low</td>
</tr>
<tr>
<td>low</td>
<td>similar to substrate 0</td>
<td>3000 psi (25 MPa)</td>
<td>4000 psi (30 MPa)</td>
<td>7500 psi (50 MPa)</td>
<td>4 x 10^6 psi (2.8 x 10^4 MPa)</td>
<td>good</td>
<td>good</td>
<td>low</td>
</tr>
<tr>
<td>low</td>
<td>similar to substrate 0</td>
<td>2000 psi (15 MPa)</td>
<td>4000 psi (30 MPa)</td>
<td>6000 psi (40 MPa)</td>
<td>2.5 x 10^6 psi (1.7 x 10^4 MPa)</td>
<td>excellent</td>
<td>N/A</td>
<td>low</td>
</tr>
<tr>
<td>moderate</td>
<td>similar to substrate 0</td>
<td>1500 psi (10 MPa)</td>
<td>3000 psi (25 MPa)</td>
<td>5000 psi (35 MPa)</td>
<td>2.5 x 10^6 psi (1.7 x 10^4 MPa)</td>
<td>excellent</td>
<td>low to moderate</td>
<td>—</td>
</tr>
<tr>
<td>low</td>
<td>similar to substrate 2000 psi (14 MPa)</td>
<td>6400 psi (44 MPa)</td>
<td>7000 psi (50 MPa)</td>
<td>8400 psi (60 MPa)</td>
<td>4.7 x 10^6 psi (2.2 x 10^4 MPa)</td>
<td>good</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>very low</td>
<td>similar to substrate 0</td>
<td>500 psi</td>
<td>2250 psi</td>
<td>4500 psi</td>
<td>3.8 x 10^6 psi</td>
<td>good</td>
<td>N/A</td>
<td>low</td>
</tr>
<tr>
<td>Substrate</td>
<td>(4 MPa)</td>
<td>(15 MPa)</td>
<td>(35 MPa)</td>
<td>(2.6 x 10^4 MPa)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>---------</td>
<td>----------</td>
<td>----------</td>
<td>------------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>1.5 to 5 x concrete</td>
<td>0 (70 MPa)</td>
<td>9000 psi</td>
<td>11000 psi</td>
<td>12000 psi</td>
<td>1.6 x 10^6 psi</td>
<td>10</td>
<td>excellent</td>
</tr>
<tr>
<td>Moderate</td>
<td>1.5 to 5 x concrete</td>
<td>4000 psi (30 MPa)</td>
<td>12000 psi (85 MPa)</td>
<td>12000 psi (85 MPa)</td>
<td>2.0 x 10^6 psi (1.4 x 10^4 MPa)</td>
<td>10</td>
<td>excellent</td>
<td>N/A</td>
</tr>
<tr>
<td>Moderate</td>
<td>similar to substrate</td>
<td>0 (5 MPa)</td>
<td>800 psi (25 MPa)</td>
<td>3500 psi (35 MPa)</td>
<td>5000 psi (35 MPa)</td>
<td>3.8 x 10^6 psi (2.6 x 10^4 MPa)</td>
<td>60</td>
<td>good</td>
</tr>
</tbody>
</table>

^4 Drying shrinkage: Very low <0.025%
Low 0.025% to 0.05%
Moderate 0.05% to 0.1%
High >0.1%

^5 Vapor is highly flammable, pungent odor may cause problems in confined or poorly ventilated spaces.
5.0 References

5.1 Referenced Standards and Reports

The standards and reports referenced were the latest editions 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 Association of State Highway and Transportation Officials (AASHTO)

www.transportation.org

Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Two Parts, Washington, DC

American Concrete Institute (ACI)

www.concrete.org

Manual of Concrete Practice, Six Parts, Farmington Hills, MI

- ACI 201.2R, “Guide to Durable Concrete.”
- ACI 302.1R, “Guide for Concrete Floor and Slab Construction.”
- ACI 364.3R, “Guide for Cementitious Repair Material Data Sheet.”
- ACI 503.5R, “Guide for the Selection of Polymer Adhesives with Concrete.”
2. ACI 515.2R, “Guide to Selecting Protective Treatments for Concrete.”
4. ACI 562, “Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings.”

ASTM International

www.astm.org

Annual Book of ASTM Standards, West Conshohocken, PA

ASTM STP 169D Significance of Tests and Properties of Concrete and Concrete Making Materials

International Concrete Repair Institute (ICRI)

www.icri.org

ICRI Publications Catalog, Rosemont, IL

U. S. Army Corps of Engineers (USACE)


Handbook for Concrete and Cement, Vicksburg, MS
5.2 Cited References

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**Beaudoin 1982**


**Do and Kim 2012**


**Emmons 1993**


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**Emmons, Vaysburd, and McDonald 1993**

Emmons, Vaysburd, and McDonald 1994


Emmons, Vaysburd, Poston, Dalrymple, and McDonald 1998


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HQUSACE 1994


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Iowa DOT 2004

Iowa Department of Transportation (2004)

http://www.iowadot.gov/operationsresearch/reports/reports_pdf/hr_and_tr/reports/tr428vol3.pdf
Iriya, Hattori, and Umehara 1999


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Iriya, K., Negi, T., Hattori, T., and Umehara, H. 2000 (Jun). “Study on Tensile Creep of Concrete at an Early Age,” *Concrete Library International*, Japan Society of Civil Engineers, No. 35, pp. 135-150.

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http://www.concreteconstruction.net/repair/flashcards-for-engineers.aspx

Pfeifer, McDonald, and Krauss 1994


Pigeon and Bissonnette 1999


U.S. Army Engineer Waterways Experiment Station, 1985, The REMR Notebook, with periodic supplements, Vicksburg, MS.

Fig. 1-1: Elements of a composite system

Fig. 3-1: Direct tensile bond test  Fig. 3-2: Shear bond test  Fig. 3-3: Slant shear bond test

If \( \varepsilon_{sh} = 0 \)

No stress occurs.

If \( \varepsilon_{sh} > 0 \)

Shear bond is stressed. Loads carried by repair are reduced; tension in repair material

Fig. 3-4: In repair applications, drying shrinkage causes stress at the interface
Fig. 3-5: Shrinkage cracks
<table>
<thead>
<tr>
<th>Magnitude, %</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.025</td>
<td>very low</td>
</tr>
<tr>
<td>0.025 to 0.05</td>
<td>low</td>
</tr>
<tr>
<td>0.05 to 0.10</td>
<td>moderate</td>
</tr>
<tr>
<td>&gt; 0.10</td>
<td>high</td>
</tr>
</tbody>
</table>

Fig. 3-6: Drying shrinkage classification
Fig. 3-7: Test results of 46 repair materials. The magnitude of variation demonstrates the need for careful investigation of actual shrinkage properties. A typical value of concrete of 0.05% was used for comparison in this study.
Given a temperature increase evenly distributed through the materials, the following stresses will occur according to the relationship of the thermal coefficients of the new and old materials.

\[
\alpha_n = \alpha_0 \quad \text{No stress occurs.}
\]

\[
\text{If } \alpha_n > \alpha_0 \quad \text{Shear bond is stressed.}
\]

Fig. 3-8: Thermal coefficient of expansion
In the absence of drying shrinkage or other considerations and given an evenly distributed load, the following stresses will occur according to the relationship of the modulus of elasticity of the new and old materials.

If $E_{\text{new}} = E_{\text{old}}$, no stress occurs.

If $E_{\text{new}} > E_{\text{old}}$, shear bond is stressed with differential displacement in the two materials. Stiffer material may become overstressed to maintain displacement compatibility in the two materials.

Fig. 3-9: Modulus of elasticity
If the old material has already developed a stable creep volume, stresses will develop according to the amount of creep occurring in the new material.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{cr} \text{ new} = 0$</td>
<td>No stress occurs.</td>
</tr>
<tr>
<td>$\varepsilon_{cr} \text{ new} &gt; 0$</td>
<td>Shear bond is stressed. Loads carried by repair are reduced.</td>
</tr>
</tbody>
</table>

Fig. 3-10: Tensile creep
Fig. 3-11: Tensile stress relief through tensile creep
Fig. 3-12: Test method for water vapor transmission
Fig. 3-13: Spalled shotcrete repair of a navigation lock wall

Fig. 3-14: Core samples from same repair
<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.01 lb/ft²</td>
<td>very good</td>
</tr>
<tr>
<td>0.01 - 0.10 lb/ft²</td>
<td>good</td>
</tr>
<tr>
<td>0.10 - 0.20 lb/ft²</td>
<td>fair</td>
</tr>
<tr>
<td>&gt; 0.20 lb/ft²</td>
<td>poor/fail</td>
</tr>
</tbody>
</table>

Fig. 3-15: Scaling resistance classification

Fig. 3-16: Cracking is often the first sign of sulfate attack
<table>
<thead>
<tr>
<th>Level of exposure</th>
<th>Sulfate content</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil</td>
<td>water</td>
</tr>
<tr>
<td>Negligible</td>
<td>under 0.1%</td>
<td>under 150 ppm (mg/liter)</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.1 to 0.2%</td>
<td>150 to 1500 ppm</td>
</tr>
<tr>
<td>Severe</td>
<td>0.2 to 2.0%</td>
<td>1500 to 10,000 ppm</td>
</tr>
<tr>
<td>Very severe</td>
<td>over 2.0%</td>
<td>over 10,000 ppm</td>
</tr>
</tbody>
</table>

Fig. 3-17: Sulfate attack classification

Fig. 3-18: Alkali silica reaction—cracks develop in cement paste surrounding reactive aggregate
Fig. 3-19: Tensile strength test methods  
Fig. 3-20: Flexural strength test methods  
Fig. 3-21: Pattern cracking develops in surfaces allowed to dry out