

ACI 546R-14

Guide to Concrete Repair

Reported by ACI Committee 546



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Guide to Concrete Repair

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Guide to Concrete Repair

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This guide presents recommendations for the selection and application of materials and methods for repairing, protecting, and strengthening concrete structures. An overview of materials and methods is presented as a guide for selecting a particular application. References are provided for obtaining in-depth information on the selected materials or methods.

Keywords: anchorage; coating; concrete repair; joint sealant; placement; polymer; protective systems; repair materials; structural strengthening.

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CHAPTER 1—INTRODUCTION

1.1—Guide use

This document provides guidance on removal and preparation, selecting material and application methods for repair, protection, and strengthening of concrete structures. The information is applicable to repairing deteriorated or damaged concrete structures; correcting design or construction deficiencies; and strengthening the structure for new uses or to comply with current, more restrictive building codes.

Current practices in concrete repair are summarized and information provided for the initial planning of repair work and selecting repair materials and methods for various conditions.

1.2—Repair methodology

The methodology for repairing a concrete structure typically includes a condition assessment of the structure, designing repairs, developing construction documents, bidding and negotiation processes, and performing the repair work. Preparing a maintenance plan for the repaired structure is also recommended. A basic understanding of the causes of concrete distress, deterioration, or deficiencies is essential to performing meaningful evaluations and completing successful repairs (ACI 364.1R). Once the cause of deterioration or deficiency is determined, the appropriate repair program can be selected to address these conditions. Depending on the cause and extent of the damage, repair is not always warranted.

Assessment of the structure should determine the cause of the deterioration or deficiency and not focus only on the symptoms. For example, cracking can be a symptom of distress that may have a variety of causes, such as restraint

of drying shrinkage, restraint of movement due to thermal cycling, overloading, corrosion of embedded metal, or inadequate design or construction. The cause of distress should be assessed for proper selection and implementation of an appropriate repair program (Fig. 1.2).

1.2.1 Condition assessment—The process of repairing a concrete structure starts with the evaluation of existing conditions. The evaluation can be divided into several steps:

- a) Reviewing available design and construction documents, previous reports, repair/maintenance records, and test data, if available;
- b) Visually examining the existing structure;
- c) Performing structural analysis of members in question or the structure in its deteriorated condition;
- d) Evaluating corrosion activity;
- e) Performing invasive or nondestructive testing, or both;
- f) Reviewing physical, chemical, and petrographic analysis results of laboratory-tested concrete samples.

Additional information on conducting condition surveys can be found in ACI 201.1R, 207.3R, 222R, 224.1R, 228.2R, 364.1R, 437R, and 562.

1.2.1.1 Unsafe conditions—During the condition assessment, conditions discovered that pose an immediate safety issue should be identified and reported to the owner for mitigation. Local building codes may require that the licensed design professional (LDP) report unsafe conditions to the authorities and typically require that the owner take measures to protect the public safety where hazardous conditions exist. For example, if loose concrete on overhead or vertical surfaces is discovered, access should be limited in the areas adjacent to and below until the hazards are removed or stabilized. If structural members exhibit compromised integrity, these members should be stabilized or the affected areas removed from service.

1.2.1.2 Global issues—The performance of a structure depends on maintaining the integrity of the structure and envelope of the building. If the LDP becomes aware of an item of concern outside the assigned scope of work that could compromise the integrity of the structure or jeopardize public safety, the appropriate parties should be notified for implementation of remedial action.

1.2.1.3 Determination of cause and extent—During the condition assessment of a structure, the cause of distress, deterioration, or deficiency should be determined. Because many deficiencies are caused by more than one mechanism, a basic understanding of the causes of concrete deterioration is essential to determine what has happened to a particular concrete structure. After completing the assessment, a suitable remedial action plan can be developed, repair applications and materials selected, and contract documents prepared. If a delay occurs between the condition survey and performing the repair work, additional deterioration and distress could occur and consideration should be given to updating the condition survey to minimize variations between estimated and actual quantities of repair work.

1.2.2 Design considerations—When designing a concrete repair, strengthening system, or protective system, the LDP should consider the safety and serviceability of the structure.

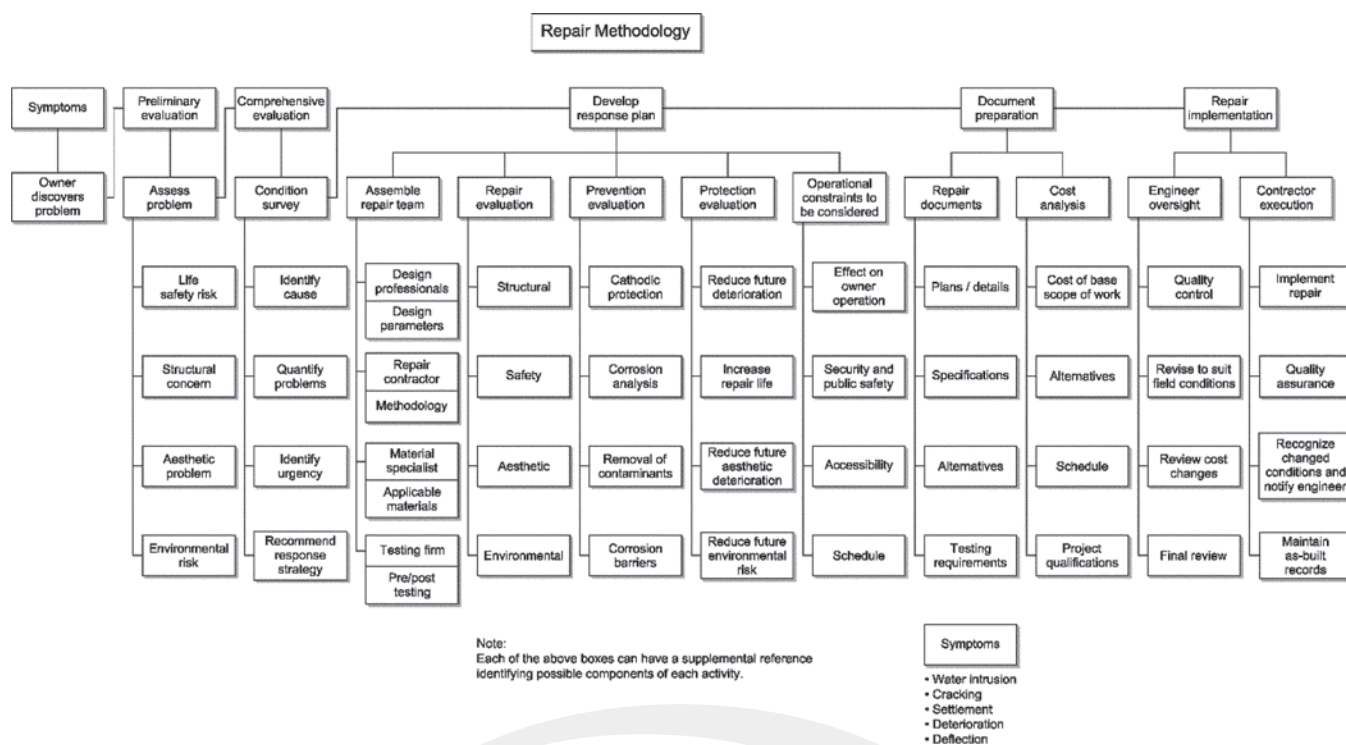


Fig. 1.2—Repair methodology.

during construction and its performance at completion. At a minimum, the repaired structure should satisfy the building code requirements for which it was designed. If required by the governing agency, the repaired structure may have to satisfy current building code requirements and be repaired and strengthened to meet these criteria. In any case, it is the LDP's responsibility to satisfy applicable code requirements for all structural components within the LDP's scope of work. Structural code provisions such as those contained in **ACI 318** may not be directly applicable to the current situation. In such cases, **ACI 562** requirements should be followed. The LDP should apply basic principles of structural mechanics and have an understanding of material behavior to evaluate and design a structural repair, a strengthening procedure, or a protective system. Several design considerations are discussed 1.2.2.1 through 1.2.2.6.

1.2.2.1 Current load distribution—In a deteriorated condition, a structural member or system may distribute dead and live loads differently than when the structure was undamaged. Cracking, deteriorated concrete, and corroded reinforcement can alter the behavior of members, leading to changes in shear, moment, and axial load distribution. As concrete and reinforcement are removed and replaced during the repair operation, these redistributed forces may be further modified. To understand the final behavior of the structural system, the engineer should evaluate the redistribution of the forces. To reestablish the original load distribution, a member can be relieved of the load by jacking or other means before repair implementation. If the structure is not jacked and the dead load is not relieved, the repaired and adjacent members may support loads differently than was assumed in the original design of the structure.

1.2.2.2 Compatibility of materials—If a repair and the existing substrate materials have the same stiffness or modulus of elasticity, the behavior of the repaired member may be assumed to be the same as the original member before deterioration or damage. Conversely, if the stiffnesses differ, then the composite nature of the repaired system should be considered. A mismatch of other material characteristics further exacerbates the effects of thermal change, vibration, long-term creep, and shrinkage. If the coefficient of thermal expansion of the repair material differs from that of the original material, stresses will be generated in both the repair and original material by temperature changes.

1.2.2.3 Creep and shrinkage—Reduction in length, area, or volume of both the repair and original materials due to creep, shrinkage, or both, affect the structure's serviceability and durability. As an example, compared with the original material, high creep or shrinkage of repair materials results in loss of stiffness of the repair, redistributed forces, and increased deformations. Controlled-shrinkage cementitious repair materials and systems can contribute to the reduction of the volume change effects.

1.2.2.4 Vibration—When the installed repair material is in a plastic state or until adequate strength has been developed, vibration of a structure can result in reduced bonding of the repair material. Isolating the repairs or eliminating the vibration may be a design consideration.

1.2.2.5 Water and vapor migration—Water or vapor migration through a concrete structure can degrade a repair. Understanding the cause of the migration and controlling it should be a repair design consideration.

1.2.2.6 Material behavior characteristics—When a repair is executed, the structural behavior of the repaired section

can differ from the behavior of the original section and is dependent on the characteristics of the repair materials. For example, if a beam's steel reinforcement has corroded extensively and has lost part of its tensile load-carrying capacity, the lost portion of the reinforcement may be replaced by external strengthening techniques (Chapter 7), such as fiber-reinforced polymer (FRP) applied externally to the tension face of the beam, following repair or replacement of the deteriorated section caused by steel corrosion. The LDP should consider the behavior and performance of the new repair under the expected service and ultimate loads, and design the repair to provide a level of safety that is at least equivalent to the original design. Such a design is outside the scope of ACI 318 and ACI 562 should be used.

1.2.3 Selecting repair methods and materials—Successful concrete repair depends on the selection and proper application of the materials and methods to be used. ACI 546.3R provides specific guidelines for the properties of repair materials and their selection and ACI 546.2R covers underwater repair materials. Repair materials and methods should be selected with the following considerations.

1.2.3.1 Concrete environment—Repair work can incorporate adjustments or modifications to remedy the cause of the concrete deterioration, such as reducing exposure to moisture, changing the water drainage pattern, eliminating sources of erosion and water infiltration, providing for differential movements, or eliminating exposure to deleterious substances. However, it is not always possible to correct causes of deterioration. For example, it may not be possible to change the environmental exposure of a concrete structure. In such cases, reasonable efforts should be made to mitigate the problem by providing appropriate protection measures.

1.2.3.2 Limiting constraints—Repair work may be affected by constraints such as limited access to the structure or areas of repair. For example, underwater concrete deterioration provides access challenges. Other constraints may include the operating schedule of the structure, weather, and limitations imposed by the owner of the structure, including repair budget.

1.2.3.3 Inherent problems—Factors that cannot be corrected, such as continued exposure to chlorides in deicing salts, salt water, or deleterious chemicals, should also be considered. In these cases, repair and protection systems extend the life of the structure but do not eliminate the causes of deterioration.

1.2.3.4 Environmental and safety requirements—These items may have a major impact on the selection of materials, methods, or both. Environmental and occupational safety constraints are governed by specific requirements and policies of owners: the Environmental Protection Agency (EPA); the Occupational, Safety, and Health Administration (OSHA); and local regulations. Refer to International Concrete Repair Institute (ICRI) 120.1 for information on further safety aspects relevant to the concrete repair industry.

1.2.3.5 Service life—The intended service life of the repaired member and structure should be considered in the selection of repair materials and methods.

1.2.3.6 Constructibility—Availability of repair materials, equipment and methods, and the technical feasibility of using them should be evaluated during the material and repair procedure selection process. Manufacturers or suppliers can provide assistance in the selection, availability, and cost of repair materials and for selecting application techniques. When selecting the appropriate repair material, consider that the technical data presented in manufacturer's literature may be incomplete and insufficient because the tests performed may not be representative of the use of the material in a particular application.

1.2.4 Temporary shoring—The repair process, including concrete removal and reinforcement repair, may alter the force and load distribution within and between reinforced concrete members. It is essential that the contractor, in conjunction with the engineer, determine the need, extent, and locations of shoring and bracing required as well as the sequence of repair to satisfy structural safety and force distribution considerations.

The need for temporary supports, shoring, bracing, and strengthening to perform the repairs should be determined before performing repair work. Concrete removal often exposes reinforcing steel that may have suffered loss of cross-sectional area; concrete removal around reinforcing steel reduces the bond between the reinforcement and the structural element, thereby reducing the shear, bending, tensile, and compression capacity or stability of the structure. Shoring and bracing may be required to address these temporary conditions.

If structural analysis is performed, the analysis should assess the effects of existing conditions and proposed repairs on the structure, including the evaluation of applicable loads and dimensional changes resulting from thermal differentials. Areas of special concern that may result in conditions that require temporary shoring and bracing include redistribution of negative moments in slabs and beams, joint and connection details, precast spandrel beams and columns, as well as live loads imposed by repair equipment and material storage.

In most cases, unless the dead and live loads are relieved via shoring before the repair work proceeds, the repaired portion of the element may not be effective in supporting loads applied after the repair installation is completed. In cases where restoration of the load-carrying capacity is a primary concern, existing loads may need to be removed and members jacked and shored to support dead loads.

1.2.5 Contract documents—The preparation of contract documents includes drawings, details, and specifications. Contract documents should include provisions specific to the project and quality assurance criteria. Because the full extent of concrete deterioration and distress may not be completely known until repair work begins, drawings and specifications for repair projects should be prepared with some flexibility regarding work items such as concrete removal, surface preparation, reinforcement replacement, and quantities of repair materials. Provisions should be included in the documents for addressing hidden conditions and providing for changes to the contract estimate and quantities.

Where deterioration is particularly severe or where extensive concrete removal is anticipated, provisions for temporary structural support should be included in the project documents. Protection of the repair site and adjacent areas may present unique problems during the execution of a repair project. Structural components and their supports in the immediate area of the repairs should be evaluated to determine if shoring, bracing, or both are required. Redistribution of member internal forces during repair is an important consideration for continuous slabs and beam-and-girder systems, and is critical for unbonded post-tensioned structures. Repair specifications should be clear and concise, delineating the scope of work, repair work items, information on existing concrete conditions if available, material and equipment requirements, surface preparation, installation procedures, quality assurance and testing criteria, and performance testing standards. Supporting documents referencing specific requirements such as tensile strength, surface profiling, compressive strength, bond strength, length change, or shrinkage behavior should be included as appropriate. Details of the concrete repair should be provided, including parameters for concrete removal and, if possible, boundaries of concrete removal and replacement along with any special features of repair system installation necessary, such as protection systems and strengthening techniques. Special attention is required for the details of reinforcement repair or replacement areas and the preparation of existing concrete before surface protection system application.

1.2.5.1 Contract types—To perform repairs, the contractor or design/build team typically enters into a contractual agreement with the owner. This contract defines the scope of work, price, and schedule. Payment for contractual requirements can be stated in lump sum or fixed-price terms, unit prices, time and material, or a combination thereof. Refer to ICRI 130.1R for further information on contract types.

1.2.5.1.1 Lump sum—This contract type is suitable for a specific, well-defined scope of work in which all repair items, quantities of work, and work conditions are known. The contractor is paid a fixed fee for completed work, regardless of the actual repair items and quantity of work performed.

1.2.5.1.2 Unit price—This contract type is suitable for a specific scope of work where all repair items are known but exact quantities are unknown. The final contract sum for the repair items covered by unit prices is based on actual quantities of the repair items properly installed by the contractor. Some individual repair items may be paid on a lump sum or time and material basis.

1.2.5.1.3 Time and material—This contract type is suitable for an undefined scope of work where both the repair items and quantities of work are undefined. The contractor is paid at a defined hourly rate for labor and reimbursed for materials and equipment with applicable overhead and profit.

1.2.5.2 Performance objectives—Repair documents should define the structural, environmental, aesthetic, and protection objectives to be achieved. Mockups are recommended where appropriate; for example, where the color or

texture is specified to match the surrounding concrete (ACI 311.1R, 311.4R, and 311.5).

1.2.6 Bid or negotiation process—Selecting a contractor is one of the most important aspects of a repair project. Contractor selection can be determined through a bidding process or negotiated directly with potential contractors. Contractor selection should be based on demonstrated evidence of expertise and successful previous experience with repairs included in the project. Manufacturer-approved installers should be considered for specialized repair products.

1.2.6.1 Prebid conference—Before bids are submitted, the engineer, owner or owner's representative, and potential contractors should attend a prebid conference to answer questions regarding the contract documents and to define expectations of the owner. This meeting should include a visit to the repair site.

1.2.6.2 Addenda—Clarifications to the contract documents based on questions raised at the prebid conference, during the bid period, or both, can be issued in addenda to the contractors before submission of bids.

1.2.7 Execution of work—Repair work should be executed in accordance with the contract documents. The concrete repair process generally consists of removing deteriorated or damaged concrete; surface preparation; repairing, supplementing, or replacing reinforcing steel; implementing specified repair techniques; and installing repair materials. Protecting the executed repairs and strengthening may also be incorporated into the repair process.

1.2.7.1 Preconstruction conference—Before starting a project, it is important to have the owner or owner's representative and LDP attend a meeting with the contractor's project manager, superintendent, and foreman to discuss the parameters, means, methods, and materials necessary to achieve the repair objectives. At this meeting, the contractor should present a construction schedule for the owner to review its acceptability and resolve any conflicts with daily operations. The frequency and types of required correspondence should be defined among all parties executing the work to communicate progress, discovered items, and construction problems.

1.2.7.2 Material submittals and shop drawings—Prior to use on the project, the contractor should submit technical, installation, and safety data for proposed repair materials in accordance with the contract documents to the LDP for review and acceptance. In addition, shop drawings for items such as shoring and bracing, reinforcing steel, specific repair methods, and repair sequencing should also be submitted by the contractor to the LDP for review and acceptance prior to initiation of the work.

1.2.7.3 Quality assurance and control—Quality assurance and control measures should be implemented to provide acceptance criteria, verify conformance to contract documents, and to verify the properties and quality of the installed repair materials. ACI 311.4R provides guidance on setup of quality control, inspection, and testing procedures. ACI 311.1R and ACI 311.5 provide guidance on inspection and testing.

1.2.7.3.1 Quality assurance—The LDP should define the quality assurance requirements in the contract documents by

establishing standards or criteria for acceptance. The quality assurance program dictates the desired level of quality for repairs.

1.2.7.3.2 Quality control, inspection, and testing—Successful completion of the repair program can be verified by implementing quality control measures during the course of the work. Such measures include:

- a) Periodic site observations by the LDP to verify general conformance with contract documents;
- b) Periodic testing by an independent testing agency to verify that requirements of the contract documents are met;
- c) Contractor supervision of the crew's work and weather conditions, including temperature, humidity, and precipitation, which may affect the repair procedure;
- d) Recordkeeping by the project team, including documentation of repair locations, repair modifications, quantities installed, documentation reviews by the LDP, weather conditions, changes to the contract documents, and periodic progress reports.

1.2.7.3.3 Testing and inspection agency qualifications—The testing agency should meet the requirements of **ASTM E329**. Inspection or testing personnel should be special inspectors, engineers, the LDP, or ACI-certified, or approved equal, field/laboratory technicians, as applicable.

1.2.7.4 Project closeout—If requested by the owner and upon completion of the project, the owner should receive and retain a project manual from the contractor or LDP containing copies of relevant contract correspondence issued during construction. The project manual should include items such as repair drawings and specifications, additional details or clarifications provided by the engineer, field and test reports, photographs, submittals, permits, change orders, requests for information (RFIs) and their responses, insurance certificates, bonds, pay applications, warranties, waivers of lien, and as-built drawings.

1.2.8 Maintenance after completion of repairs—Maintenance of the concrete structure and any protection or strengthening system is recommended after completion of a concrete repair project. Lack of adequate maintenance may result in premature failure of the repair or surrounding areas. If requested by the owner, the LDP should develop a maintenance manual for repair work.

1.2.8.1 Warranty coverage—Warranty requirements should be followed, including periodic inspections or recoating of membranes and sealers to ensure that warranty coverage is maintained. Warranty items should be reviewed during the warranty period and the contractor contacted to repair failures that occur under warranty.

1.2.8.2 Periodic inspections—Continued evaluation of the structure through periodic engineering reviews should be considered to monitor structural integrity and performance of repairs.

1.2.8.3 Post-repair monitoring systems—Systems to detect concrete/system failures should be considered, such as corrosion monitoring for detecting corrosion and acoustic monitoring for detecting tendon failures, in post-tensioned structures.

1.3—Sustainability

A green structure is an environmentally sustainable structure designed, constructed, and maintained to minimize its impact on the environment (**Schokker 2010**). The primary objectives when designing a green structure include reducing energy consumption, conserving water, and recycling waste. Repairing and maintaining concrete structures instead of replacement is a green concept and a sustainable philosophy. Repairing concrete structures meets sustainability objectives by conserving existing materials and thereby reducing energy consumption and material waste.

CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," <http://www.concrete.org/Tools/ConcreteTerminology.aspx>. Additional concrete repair definitions are found in the International Concrete Repair Institute (ICRI) terminology database, <http://www.icri.org/GENERAL/repairterminology.aspx>.

CHAPTER 3—CONCRETE REMOVAL AND SURFACE PREPARATION

3.1—Introduction

This chapter covers the removal of deteriorated and sound concrete, and preparation of the concrete surface to receive new repair materials. Exercising care during the removal and preparation phases of a repair project can be the most important factor in ensuring the longevity of the repair, regardless of the material or technique used. Concrete should be removed carefully so as not to damage the existing adjacent concrete or affect bond of the new repair material.

Care should be taken when removing concrete around prestressing steel, both bonded and unbonded strands. When high-energy impact tools such as chipping hammers are used, operators should avoid contacting the strands with the tools, as such contact may cause wires to rupture, possibly leading to strand failure and a reduction in the structure's load capacity. Removing surface concrete may also cause excessive stresses in the concrete to remain and redistribute secondary forces and moments in indeterminate structures. The extent of concrete removal should not be permitted to exceed stress limits in the remaining concrete.

Personal protective equipment should be used in all processes and the containment, handling, and disposal of concrete dust, slurry, and debris considered with the processes employed. Refer to **ICRI 120.1** for recommendations on safety in the concrete repair industry to minimize vibrations and noise.

3.2—Concrete removal

A repair project typically involves removing deteriorated, damaged, or defective concrete. In most cases, however, determining the extent of the deteriorated or damaged concrete requiring removal can be difficult. Common techniques to identify distressed concrete are sounding by hammer tapping or by chain drag (**ASTM D 1585**). Delaminations and microcracks may not be detected by

hammer sounding or chain dragging. Other techniques include impact-echo testing (**ASTM C1383**), ground-penetrating radar (GPR) (**ASTM D6087**), and infrared thermography (**ASTM D4788**), typically accompanied by sounding by hammer tapping, chain drag, or impulse response. Refer to **ACI 228.2R** and **ICRI 210.4** for additional information and other test methods used to identify deteriorated and damaged concrete.

Removing concrete using aggressive methods can damage concrete that is intended to remain in place. For example, blasting with explosives or the use of heavy impact equipment can result in additional concrete delamination or cracking. Impact equipment with a blunt-tipped removal apparatus can cause more delamination and cracking than sharp-tipped tools. Removing concrete using impact tools may also result in microcracking or bruising (**Hindo 1990**) to the surface concrete left in place. Unless this damaged layer is removed, the substrate concrete will be weakened, possibly resulting in reduced bond strength between the substrate concrete and repair material. Thus, removing all damaged or delaminated concrete, including bruising, at the interface of the repair and the substrate concrete is an important part of achieving a strong bond and composite action between the substrate concrete and the repair material. If all deteriorated and damaged concrete is not removed, then the possibility of repair failure is increased, even if a high-quality repair material is used.

In most cases in which concrete has been removed from a structure by primary means, such as impact methods, the concrete left in place should be prepared by a secondary method, such as abrasive blasting or high-pressure water jetting, to remove any remaining damaged and microcracked surface material. Careful visual inspection and sounding of prepared surfaces should be conducted and loose, delaminated, or unsound concrete should be removed before placing repair materials. The suitability of the substrate to receive the repair material can be verified by tensile pull-off testing of trial repairs (**ICRI 210.3**; **ASTM C1583**).

Localized removal of deteriorated concrete in a member includes squaring the edges of the repair area by saw cutting or chipping square to avoid feather edging the repair material, removal of delaminated and unsound concrete, and removal of sound concrete as necessary to provide a minimum thickness of repair material throughout the repair area. Feather edging of repair materials should be avoided. For shotcrete repairs, the edges of the removal areas should taper toward the center of the removal area to avoid acute angles that can make shotcrete placement more difficult (**ACI 506R**). Reentrant corners in the perimeter of removal areas should be avoided. Large variations in the depth of removal within short distances should also be avoided, as they may result in cracking due to varying behavior of the repair materials with different thicknesses.

Unless otherwise directed by the project specifications, existing reinforcement should not be cut. Reviewing drawings and using a cover meter or similar device to obtain data as to the location and depth of existing reinforcement are good practice. In addition, removing deteriorated and

damaged concrete is commonly performed before saw cutting to determine the location and depth of reinforcement.

3.2.1 General considerations—Concrete repair requires removal of deteriorated and damaged material. Removing sound concrete, however, may also be necessary to ensure that all unsound or contaminated material is removed, facilitate structural modifications, provide adequate repair geometry and configuration, and provide development and encapsulation of reinforcing steel and embedded items. Some methods may be more effective in sound concrete, whereas others may work better for deteriorated and damaged concrete.

Concrete removal techniques should be effective, safe for the structure and the construction workers, economical, suited to the requirements of the owner, environmentally friendly, and minimize damage to the concrete left in place. The removal technique chosen may have a significant effect on the length of time that a structure will be out of service for the repair. Some techniques may permit a portion of the repair work to be accomplished without removing the structure from service. The same removal technique, however, may not be suitable for all portions of a given structure. In some instances, a combination of removal techniques may be more appropriate to speed removal and limit damage to the existing concrete. Field testing mockups of selected removal techniques can help determine the best procedures to use for the repair.

In general, the engineer responsible for the design of the repair should specify the objectives to be achieved by the concrete removal, and the repair contractor should be allowed to select the most effective removal method subject to the engineer's acceptance. In some instances, however, the engineer may need to specify the removal techniques necessary for the repair and those prohibited due to constraints and logistics of the structure.

The size, quantity, and location of reinforcing steel; size and type of aggregates; concrete compressive strength modulus of elasticity as well as the presence of existing coatings, toppings, overlays; and other existing or as-built conditions are important information to consider in determining the effective method(s) and cost of concrete removal. Whenever possible, this information should be made available to contractors during bidding. This information is also beneficial to the engineer when they specify concrete removal and surface preparation criteria and for select repair materials.

3.2.2 Temporary shoring—It is essential to evaluate the removal operations and their impact on the structure's integrity throughout the repair process and to limit the extent of damage to the structure and the existing concrete that remains. Before removing concrete, the need for temporary supports, shoring, bracing, and strengthening should be assessed (Fig. 3.2.2a). Structural elements to be repaired may require temporary shoring, removal of applied loads, or both, to prevent damaging structural deformations, buckling or movement of reinforcement, or possible collapse. A structural analysis may need to be performed to assess the effects of existing conditions and proposed repairs on the structural integrity of the building and the need for temporary shoring.



Fig. 3.2.2a—Temporary shoring parking garage floor (left) and balcony slabs (right).

Care should be used during removal of concrete to avoid cutting and damaging existing reinforcing steel (Fig. 3.2.2b). Because embedded reinforcement may not be located in the specified position and is not visible before concrete removal, unanticipated damage can occur when saw cutting and removing concrete. This damage, as well as excess concrete removal, could affect structural integrity during repairs and the need for temporary shoring.

3.2.3 Quantity of concrete to be removed—In most repair projects, all damaged or deteriorated concrete should be removed because deterioration continues with time. The anticipated quantity of concrete removal is directly related to the extent of the distress, repair or removal technique, and elapsed time between the initial survey and repair construction; potential quantity overruns may be realized between preparation of the quantity estimates and actual removal. Estimating inaccuracies can be minimized by a thorough condition survey performed as close as practical to the time the repair work is executed. When, by necessity, the condition survey is performed far in advance of the repair work, estimated removal quantities should be increased to account for continued deterioration. Because most concrete repair projects are based on unit prices, repair areas should be accurately measured upon completion of the work. This is typically done jointly by the engineer and the contractor. It is not uncommon for final measured quantities to exceed the initial estimated quantities. Refer to **ICRI 130.1R** for guidelines for methods of measurement for concrete repair work.

3.2.3.1 Anodic ring (halo) effect—Accelerated corrosion occurs where reinforcement located in existing contaminated concrete extends into repair area containing uncontaminated repair material due to the difference in electrical potential between the contaminated and uncontaminated concrete volumes (6.2.5). In general, concrete removal should continue until no further delamination, cracking, or significant corrosion is observed along the reinforcing steel. Additional measures should be considered to minimize future concrete damage due to corrosion if chloride contamination or carbonated concrete will remain beyond the repair area. Concrete excavation that damages the bond of the reinforcing steel to the existing concrete requires additional concrete removal and undercutting of the reinforcing steel.



Fig. 3.2.2b—Saw cutting perimeter of repair area.

3.2.3.2 Removal of concrete surrounding reinforcing steel—Concrete removal should include the removal of deteriorated and damaged concrete surrounding existing reinforcing steel. Care should be used to prevent further damage to the reinforcing or prestressing steel caused by the process of removing the concrete. For this reason, a cover meter or reinforcing bar locator, along with structural drawings if available, should be used to help determine the depth, size, quantity, and approximate location of the existing reinforcement within the repair area.

Once the selected concrete has been removed within the repair area, a less invasive removal method, such as light (15 lb [67 N]) chipping hammers should be used to remove the concrete around exposed reinforcement. Care should be taken to not damage the reinforcement or otherwise cause loss of reinforcing bond to the existing remaining concrete. If the existing reinforcing steel is only partially exposed after concrete removal, it may not be necessary to remove additional concrete to expose the full circumference of the reinforcement, provided the reinforcement is uncorroded, has not lost bond to the existing concrete; the existing concrete is sound and not chloride-contaminated (**AASHTO T 260**, **ASTM C1152**, and **ASTM C1218**); and the pH (**ASTM F710**) has not been affected by carbonation (6.2.4) or acid attack. When the exposed reinforcing steel has loose rust,

corrosion products, is not well bonded to the surrounding concrete, or if the concrete surrounding the reinforcing steel is chloride-contaminated, concrete removal should continue around the reinforcing steel to create a minimum of 0.75 in. (19 mm) clearance to the surrounding concrete or 0.25 in. (6 mm) larger than the coarsest aggregate in the repair material. Undercutting the exposed reinforcing steel provides clearance around the reinforcing steel for cleaning, complete bonding of the repair material to the existing concrete, and structurally secures the repair (ICRI 310.1R). Pay special attention when removing concrete around both bonded and unbonded prestressed steel strands. Excessive concrete removal can lead to changes in strand profile, reduce forces in the strand, and compromise the integrity of the structure.

3.2.3.3 Preparation of repair perimeter—Following the removal of unsound concrete, the perimeter of the repair area should be saw cut to create a simple symmetrical configuration, preferably square or rectangular with square corners. Saw cut to a depth of 0.50 to 0.75 in. (13 to 19 mm) at the repair perimeter to provide a vertical edge for consolidating the repair material. Saw cutting to a lesser depth may be necessary at locations where the reinforcing steel has reduced concrete cover. A perimeter saw cut is often unnecessary with concrete removal methods such as high-pressure water jets. Refer to the manufacturer's recommendations for the selected repair material. Following saw cutting, some removal of sound concrete may be required to achieve the repair perimeter. Care should be taken to avoid abrupt changes in depth within the repair area, as the repair material is more susceptible to cracking at these locations.

3.2.4 Concrete removal methods—Removal and excavation methods can be categorized by the way in which the process acts on the concrete. Common processes are cutting, impacting, and high-pressure water jets (hydrodemolition). Other less-common methods of concrete removal are also available, including blasting and presplitting methods, but are typically only used for large-scale concrete removal. Table 3.2.4 provides a general description of these processes, lists the specific removal techniques within each category, and provides a summary of information on each technique. Refer to ICRI 310.1R, 310.2R and Society for Protective Coating (SSPC)-SP13/NACE 6 for additional information on concrete removal.

3.2.4.1 Cutting methods—Cutting methods generally employ mechanical sawing or high-pressure water jets to cut around the perimeter of concrete sections to permit their removal. The size of the sections cut free is governed by the available lifting and transporting equipment. The cutting methods include high-pressure water jets, saw cutting, diamond wire cutting, mechanical shearing, and stitch drilling.

3.2.4.1.1 High-pressure water jet without abrasives—A narrow high-pressure water jet driven at high velocities, commonly producing pressures of 10,000 to 40,000 psi (69 to 276 MPa) to cut and remove concrete and prepare concrete surfaces. Section 3.2.4.3 describes using a water jet as a concrete removal method. High-pressure water jets without abrasives will remove concrete but will not cut or damage the reinforcing steel. The addition of abrasives to

the water jet can result in cutting of the concrete and the reinforcing steel.

3.2.4.1.2 Saw cutting—Diamond or carbide saws are available in sizes ranging from small and capable of being hand-held, to large and capable of cutting depths of approximately 5 ft (1.5 m) to substantially larger depths.

3.2.4.1.3 Diamond wire cutting—Diamond wire cutting is accomplished with a wire containing nodules (small lumps) impregnated with diamonds. The wire is wrapped around the concrete mass to be cut and connected with a power pack to form a continuous loop. The loop is spun in the plane of the cut while being drawn through the concrete member. This system can be used to cut a structure of any size as long as the wire can be wrapped around the concrete. The limits of the power source determine the size of the concrete structure that can be cut. This system provides an efficient method for cutting and dismantling large or small concrete structures.

3.2.4.1.4 Mechanical shearing—The mechanical shearing method uses hydraulically powered jaws to cut or crush concrete and shear the reinforcing steel. This method is applicable for making cutouts through slabs, decks, and other thin concrete members and especially applicable where total demolition of the member is desired. The major limitation of this method is that cuts need to start from free edges or from holes made by hand-held breakers or other means.

3.2.4.1.5 Stitch drilling—The stitch drilling method uses overlapping boreholes along the removal perimeter to cut out sections. This method is applicable for making cutouts in concrete members where access to only one face is possible, and the depth of cut is greater than can be economically cut by the saw cutting and diamond wire cutting methods. The primary drawback of stitch drilling is the potential for costly removal complications if the cutting depth exceeds the accuracy of the drilling equipment, so that uncut concrete remains between adjacent holes.

3.2.4.2 Impact methods—Impact methods are the most commonly used concrete removal techniques. Impact methods involve striking a concrete surface repeatedly with a high-energy tool with hardened points or large mass to fracture and spall the concrete. Using impact methods for concrete removal can result in microcracking of the surface concrete left in place and creating a weakened plane below the bond line of the repair material. Impact methods also transmit vibrations through the structure and reinforcing steel, which may cause further damage and loss of bond between the reinforcing steel and existing concrete. Factors such as the weight, size, and power of the impact removal equipment should be considered, balancing the desire for productive removal while minimizing damage and microcracking. Secondary methods, such as abrasive blasting and water blasting, should be considered to remove microcracking following the use of impact methods. Tensile pull-off testing in accordance with ICRI 210.3 or ASTM C1583 is recommended to determine the suitability of the final prepared surface to receive repair materials and coatings.

3.2.4.2.1 Hand-held breakers—The hand-held breaker or chipping hammer is probably the most commonly known of all concrete removal devices. Hand-held breakers

Table 3.2.4—Summary of features, considerations, and limitations for concrete removal methods

Category	Features	Considerations/limitations
Water-jet cutting (uses perimeter cuts to remove large pieces of concrete)	a) High-pressure water jet without abrasives b) Applicable for making cutouts through slabs, decks, and other thin concrete members c) Cuts irregular and curved shapes d) Makes cutouts without overcutting corners e) Cuts flush with intersecting surfaces f) No heat, vibration, or dust is produced g) Handling of debris is efficient because bulk of concrete is removed in large pieces	a) Cutouts for removal limited to thin sections b) Cutting is typically slower and more costly than diamond blade sawing c) Moderate levels of noise may be produced d) Controlling flow of waste water may be required e) Additional safety precautions are required due to the high water pressure produced by the system f) Does not cut reinforcing steel
Saw cutting (applicable for making cutouts through slabs, decks, and other thin concrete members)	a) Makes precision cuts b) No vibration is produced c) Handling of debris is efficient because bulk of concrete is removed in large pieces	a) Cutouts for removal limited to thin sections b) Performance is affected by type of diamonds and the diamond-to-metal bond in blade segments (segment selection is based on aggregate hardness) c) The higher the percentage of steel reinforcement in cuts, the slower and more costly the cutting d) The harder the aggregate, the slower and more costly the cutting e) Controlling flow of waste water may be required
Diamond wire cutting (applicable for cutting large, thick pieces of concrete)	a) The diamond wire chain can be any length b) No dust or vibration is produced c) Large blocks of concrete can be lifted out by a crane or other mechanical methods d) The cutting operation can be efficient in any direction	a) The cutting chain must be continuous b) Access to drill holes through the concrete must be available or access around the full section of the structure if the full section is to be cut c) Water must be available to the chain d) Controlling the flow of waste water may be required e) The harder the aggregate or concrete, and the higher the percentage of steel, the slower and more costly the cutting f) Performance is affected by the quality, type, and number of diamonds as well as the diamond-to-metal bond in the chain.
Mechanical shearing (applicable for making cutouts through slabs, decks, and other thin concrete members)	a) Steel reinforcement can be cut b) Limited noise and vibration are produced c) Handling of debris is efficient because bulk of concrete is removed in large pieces	a) Limited to thin sections where an edge is available or a hole can be made to start the cut b) Exposed reinforcing steel is damaged beyond reuse c) Remaining concrete is damaged d) Extremely rugged profile is produced at the cut edge e) Ragged feather edges remain after removal
Stitch drilling (applicable for making cutouts through concrete members where access to only one face is feasible)	a) Handling of debris is more efficient because bulk of concrete is removed in large pieces	a) Rotary-percussion drilling is more expedient and economical than diamond core drilling; however, it may result in more damage to the concrete that remains, especially at the point of exit from the concrete b) Depth of cuts is dependent on accuracy of drilling equipment in maintaining overlap between holes with depth and diameter of the boreholes drilled. The deeper the cut, the greater borehole diameter required to maintain overlap between adjacent holes and the greater the cost c) Uncut portions between adjacent boreholes will hamper or prevent the removal d) Cutting reinforced concrete increases the cutting time and increases the cost. Aggregate toughness for percussion drilling and aggregate hardness for diamond coring will affect cutting cost and rate. e) Personnel must wear hearing protection due to high noise levels.
Impacting (uses repeated striking of the surface with a mass to fracture and spall the concrete)	a) Hand-held breakers b) Applicable for limited volumes of concrete removal c) Applicable where blow energy must be limited d) Widely available commercially e) Can be used in areas of limited work space f) Produces relatively small and easily handled debris	a) Performance is a function of concrete soundness and aggregate toughness b) Significant loss of productivity occurs when breaking action is other than downward c) Removal boundaries will likely require saw cutting to avoid feathered edges d) Concrete that remains may be damaged (microcracking) e) Produces high levels of noise, dust, and vibration
Boom-mounted breakers (applicable for full-depth removal of slabs, decks, and other thin concrete members and for surface removal from more massive concrete structures)	a) Can be used for vertical and overhead surfaces b) Widely available commercially c) Produces easily handled debris	a) Blow energy delivered to the concrete may have to be limited to protect the structure being repaired and the surrounding structures from damage b) Performance is a function of concrete soundness and aggregate toughness c) Damages remaining concrete d) Damages reinforcing steel e) Produces feathered edges f) Produces high level of noise and dust

Table 3.2.4 (cont.)—Summary of features, considerations, and limitations for concrete removal methods

Category	Features	Considerations/limitations
Scabblers	a) Low initial cost b) Can be operated by unskilled labor c) Can be used in areas of limited work space d) Removes deteriorated concrete from wall or floor surfaces efficiently e) Readily available commercially	a) High cyclic energy applied to a structure will produce fractures in the surface of the remaining concrete b) Produces high level of noise and dust c) Limited depth removal
Needle scaler (applicable for limited volumes of concrete removal)	a) Can be used in areas of limited work space b) Can be used for vertical and overhead surfaces c) Produces relatively small and easily handled debris	a) Limited concrete removal depth b) Concrete that remains can be damaged (microcracking) c) Produces feathered edges
Scarifier/milling (applicable for removing deteriorated concrete surfaces from slabs, decks, and mass concrete)	a) Boom-mounted cutters are applicable for removal from wall and ceiling surfaces b) Removal profile can be controlled c) Method produces relatively small and easily handled debris	a) Removal is limited to concrete without steel reinforcement b) Sound concrete reduces the rate of removal c) Can damage concrete that remains (microcracking) d) Noise, vibration, and dust are produced
Erosion/expansive pressure (hydrodemolition) (applicable for removal of deteriorated concrete from surfaces of bridges and parking decks and other deteriorated surfaces where removal depth is 6 in. [150 mm] or less)	a) Does not damage the concrete that remains b) Steel reinforcement is left clean and undamaged for reuse c) Method produces easily handled aggregate-sized debris	a) Productivity is reduced when sound concrete is being removed b) Removal profile will vary with changes in depth of deterioration c) Method requires large source of potable water to meet water demand d) Waste water may have to be controlled e) A permit may be required if waste water is to enter a waterway f) Personnel must wear hearing protection due to the high level of noise produced g) Flying debris is produced h) Additional safety requirements are required due to the high pressures produced by these systems
Blasting—explosives (uses rapidly expanding gas confined within a series of boreholes to produce controlled fracture and removal of concrete)	a) Most expedient method for removing large volumes where concrete section is 10 in. (250 mm) thick or more b) Produces good fragmentation of concrete debris for easy removal	a) Requires highly skilled personnel for design and execution b) Stringent safety regulations must be complied with regarding the transportation, storage, and use of explosives due to their inherent dangers c) Blast energy must be controlled to avoid damage to surrounding structures resulting from air-blast pressure, ground vibration, and flying debris
Presplitting (uses hydraulic jacks, water pulses, or expansive agents in a pattern of boreholes to presplit and fracture the concrete to facilitate removal)	a) Large sections can be presplit for removal, thereby making handling of debris more efficient b) Development of presplitting plane in direction of boreholes depth is limited c) Development of presplitting plane is decreased by presence of reinforcing steel normal to presplitting plane d) Presplit opening must be wide enough to allow cutting of steel reinforcement e) Secondary means of breakage may be required to complete removal a) Loss of control of presplitting plane can result if boreholes are too far apart or if holes are located in severely deteriorated concrete	a) Development of presplitting plane is decreased by presence of reinforcing steel normal to presplitting plane b) Presplit opening must be wide enough to allow cutting of steel reinforcement c) Secondary means of breakage may be required to complete removal d) Loss of control of presplitting plane can result if boreholes are too far apart or if holes are located in severely deteriorated concrete
Hydraulic splitter (applicable for presplitting slabs, decks, walls, and other thin to medium concrete members)	a) Typically less costly than cutting members b) Direction of presplitting can be controlled by orientation of wedges and drill hole layout c) Can be used in areas of limited access d) Limited skills required by operator e) No vibration, noise, or fly rock is produced except by the drilling of boreholes and secondary breakage method	
Water pulse splitter	a) Economical, portable, rugged, and easy to use and maintain b) Devices have self-contained power sources c) Negligible vibration	a) Requires boreholes at close intervals to control crack propagation b) Control of crack plane depth is limited c) Not applicable to vertical surfaces d) Produces some noise e) Drill holes must hold water
Expansive agents (applicable where 9 in. [230 mm] or more of a concrete face is to be removed)	a) Can be used to produce vertical splitting planes of significant depth b) No vibration, noise, or flying debris is produced other than that produced by the drilling of boreholes and secondary breakage method	a) Best used in gravity-filled vertical or near-vertical holes b) Agents of putty consistency are available for use in horizontal or overhead holes c) Development of presplitting plane is decreased by presence of reinforcing steel normal to presplitting plane



Fig. 3.2.4.2.1—Hand-held breakers.

are available in various sizes with different levels of energy and efficiency (Fig. 3.2.4.2.1). These tools are generally defined by weight and vary in size from 8 to 90 lb (3.5 to 41 kg). Note that the larger the hammer, the greater the potential for microcracking. Smaller hand-held breakers are commonly used in partial depth removal of sound and unsound concrete and concrete removal around reinforcing steel because they minimize damage to the existing concrete and reinforcing steel. Larger breakers are used for removal of large volumes of concrete. Exercise care when selecting the size of breakers to minimize damage to the structure and to avoid shattering or breaking through the remaining section. Sharp-pointed tools also tend to reduce the potential for microcracking of the surface concrete left in place, as do lightweight breakers used at a shallower angle to the removal substrate.

3.2.4.2.2 Boom-mounted breakers—The boom-mounted breaker is similar to the hand-held breaker except that it is mechanically operated and considerably larger than a hand-held breaker (Fig. 3.2.4.2.2). Boom-mounted breakers differ from hand-held breakers as they function on the principle of high energy and low frequency rather than low energy and high frequency, and are driven by compressed air or hydraulic pressure. The reach of the hydraulic arm enables the breaker to be used on vertical or overhead surfaces at a considerable distance above and below the machine level. The boom-mounted breaker is a highly productive means of removing concrete; however, the high-cycle impact energy delivered to a structure by the breaker generates forces that may damage the existing concrete and reinforcing steel and adversely affect the integrity of the structure.

3.2.4.2.3 Scabblers—Scabblers are best known for their ability to remove shallow depths of concrete from a surface. Scabblers impact the concrete with cutting heads to create a chipping and pulverizing action. Scabbler heads are available in various sizes and geometrical shapes, and varying numbers of heads may be mounted on the cylinders. Equipment size depends on the number of cylinders. The equipment is normally driven by compressed air. A scabbler is designed to remove deteriorated or sound concrete from



Fig. 3.2.4.2.2—Boom-mounted breaker.

horizontal, vertical, and overhead surfaces to relatively shallow depths (1/8 to 3/4 in. [3 to 19 mm]). Scabblers produce a very irregular surface with a fractured coarse aggregate profile and typically cause microcracking of the concrete surface. Scabblers can also remove brittle coatings and provide deep profiling in preparation for overlays and other repair materials.

3.2.4.2.4 Needle scaler—Needle scaling uses the pointed tips of a bundle of steel rods contained by a steel tube to impact and remove concrete to shallow depths (1/16 to 1/8 in. [1.5 to 3 mm]) at horizontal, vertical, and overhead surfaces. This method is typically used at edges and areas inaccessible by larger equipment. Needle scaling creates the potential for microcracking of the concrete surface. Needle scalars are also used for removing existing coatings and preparation of surfaces for coatings and thin overlays.

3.2.4.2.5 Scarifier—A scarifier is a concrete removal device that uses rotary action and several cutter bits mounted on a drum to fracture and pulverize the concrete from a surface. Concrete removal depths typically range from 1/8 to 3/4 in. (3 to 19 mm) and may require multiple passes with the equipment. Scarifying can remove deteriorated and sound concrete in which some of the concrete contains form ties and wire mesh. Scarifiers are available in a range of sizes for removing deteriorated concrete on horizontal, vertical, and overhead surfaces. Advantages include well-defined limits of concrete removal, relatively small and easily handled concrete debris, and simplicity of operation. Scarifiers may cause microcracking in the concrete. Scarifiers are also used for the removal of brittle coatings and adhesives, and profiling of concrete surfaces in preparation for high-build coatings, overlays, and other repair materials.

3.2.4.2.6 Milling methods—Milling methods can remove a specified amount of concrete from large areas of horizontal or vertical surfaces. The removal depth typically ranges from 1/4 to 4 in. (6 to 100 mm). Removal depth is determined by the number and size of teeth. Milling operations typically leave a sound surface with fewer microfractures than impact methods (Virginia Transportation Research

Council 2001). Tensile pull-off testing is recommended on surfaces prepared by milling to determine the suitability of the surface to receive repair materials.

3.2.4.3 Hydrodemolition—High-pressure water jetting (hydrodemolition) can be used to remove sound and unsound concrete on horizontal, vertical, and overhead surfaces without damaging the existing reinforcing steel and without causing microcracking of the remaining in-place concrete. Hydrodemolition disintegrates concrete and leaves a saturated, rough, irregular surface profile capable of providing an excellent composite bond with the repair material (Fig. 3.2.4.3). The method is very efficient at removing unsound concrete over large areas of the concrete surface cleaning the reinforcing steel in the process by abrasive action of the water and the pulverized concrete. The existing concrete surface is ready for placement of the repair material, provided the surface is thoroughly cleaned and rinsed following hydrodemolition and any ponded water is removed. Hydrodemolition uses high-pressure pumps capable of generating pressures from 10,000 to 40,000 psi (69 to 276 MPa) with water flow rates between 6 to 100 gpm (25 and 380 lpm) (ICRI 310.3). The high-pressure water jet may be applied using a robotic removal unit. The robotic unit moves the water jet uniformly over the concrete to be removed. Hydrodemolition can also remove deteriorated concrete that exists below the specified removal depth. This is called selective removal and it is used to help ensure that all unsound concrete has been removed. The water jet does not transmit vibration into the concrete and will not cause further damage to the existing structure. Hydrodemolition is a wet process that minimizes dust from the work area and uses large quantities of water that must be collected and disposed of properly. Wastewater contains suspended particles and typically has a pH of 11 to 12.5. The wastewater must be filtered and treated to reduce the particulates and the alkalinity reduced to a pH typically between 5 and 10 before discharge. Hydrodemolition should not be used in post-tensioned structures with unbonded tendons, except under the direct supervision of a structural engineer.

Water jet hand lances operating at pressures of 10,000 to 40,000 psi (69 to 276 MPa) with water flows of 2 to 12 gpm (8 to 45 lpm) are available to remove concrete in areas difficult to access with larger equipment (ICRI 310.3; SHRP-S-336).

Hydrodemolition is also used to remove coatings and waterproofing membrane systems. This removal is generally accomplished with a multiple-jet nozzle instead of the single-jet nozzle (ICRI 310.3; ACI RAP-14). Hydrodemolition is also used in surface preparation for overlays.

Typically, this method is not used for small-scale repairs primarily for reasons of practicality, containment, and equipment mobilization. Additionally, large volumes of water are required for this method as well as the subsequent water treatment and disposal.

3.2.4.4 Blasting methods—Blasting methods generally use rapidly expanding gas confined within a series of bore holes to produce controlled fractures and removal of the concrete.

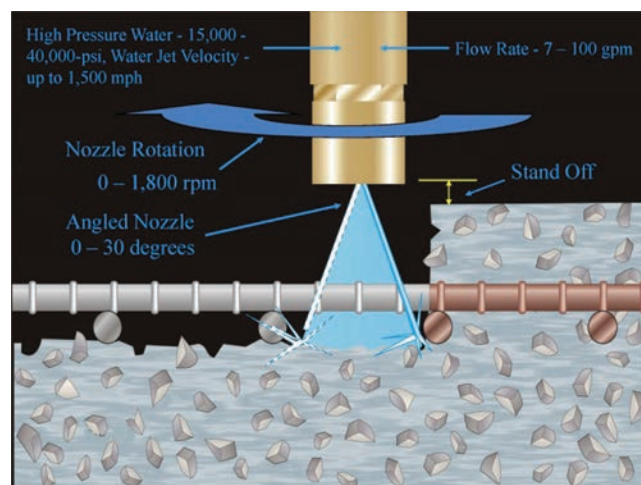


Fig. 3.2.4.3—Hydrodemolition.

The only blasting method addressed in this report is explosive blasting.

Explosive blasting is the most cost-effective and expedient means for removing large quantities of concrete. An example is portions of large mass concrete foundations or walls. This method involves drilling bore holes, placing an explosive in each hole, and detonating the explosive. Controlled-blasting techniques minimize damage to the material that remains after blasting. One such technique (cushion blasting) involves drilling a line of 3 in. (75 mm) diameter or smaller bore holes parallel to the removal face, loading each hole with light charges of explosive (typically a detonating cord) distributed along its length, cushioning the charges by stemming each hole completely or in the collar with wet sand, and detonating the explosive with electric blasting caps. The uniform distribution and cushioning of the light charges produce a relatively sound surface with little overbreak.

Blasting machines and electrical blasting-cap delay series are also used for controlled demolition and use proper timing sequences to provide greater control in reducing ground vibration. Controlled blasting has been used successfully on numerous repair projects. Selecting the proper charge weight, borehole diameter, and borehole spacing for a repair project depends on the location of the structure, the acceptable degree of vibration and damage, and the quantity and quality of concrete to be removed. If at all possible, a pilot test program should be implemented to determine the optimum parameters. Because of the inherent dangers in the handling and usage of explosives, all phases of the blasting project should be performed by qualified licensed personnel with proven experience and ability.

3.2.4.5 Presplitting methods—Presplitting methods use hydraulic splitters, water pressure pulses, or expansive chemicals used in bore holes drilled at points along a predetermined line to induce a crack plane for the removal of concrete. The pattern, spacing, and depth of the bore holes affect the direction and extent of the crack planes that propagate. Presplitting is generally used in mass concrete structures or unreinforced concrete.

3.2.4.5.1 Hydraulic splitter—A hydraulic splitter is a wedging device used in predrilled bore holes to split concrete into sections. This method has potential as a primary means for removal of large volumes of material from mass concrete structures. Secondary means of separating and handling the concrete, however, may be required where reinforcing steel is involved.

3.2.4.5.2 Water-pulse splitter—The water-pressure pulse method requires that the boreholes be filled with water. A device, or devices, containing a very small explosive charge is placed into one or more holes, and the explosive is detonated. The explosion creates a high-pressure pulse that is transmitted through the water to the structure, cracking the concrete. Secondary means may be required to complete the removal of reinforced concrete. This method does not work if the concrete is so badly cracked or deteriorated that it does not hold water in the drill holes.

3.2.4.5.3 Expansive product agents—Commercially available cementitious expansive products, when correctly mixed with water, exhibit a large increase in volume over a short period of time. By placing the expansive agent in boreholes located in a predetermined pattern within a concrete structure, the concrete can be split in a controlled manner for removal. This technique has potential as a primary means of removing large volumes of material from concrete structures and is best suited for use in holes of depth greater than 12 in. (300 mm). Secondary means may be required to complete the separation and removal of concrete from the reinforcement. A key advantage to the use of expansive agents is the relatively nonviolent nature of the process and the reduced tendency to disturb the adjacent concrete.

3.3—Surface preparation

Following concrete removal, the most important step in the repair of a concrete structure is the surface preparation and cleanliness of the repair area. Regardless of the nature, sophistication, or cost of the repair material, the repair is only as good as the surface preparation. To ensure the desired behavior in the structure, repairs to reinforced concrete should also include proper preparation of the reinforcing steel and concrete surface to develop a good bond with the repair material. This section discusses the surface preparation of concrete and reinforcing steel for a repair. Project documents should include requirements for inspection of substrates to confirm adequate completion of preparation measures prior to placement of the repair materials.

3.3.1 General considerations—Surface preparation consists of the final steps necessary to prepare the concrete surface to receive repair materials. The appropriate preparation of the concrete surface depends on the procedures used to remove the concrete and on the type of repair to be undertaken.

Most of the concrete removal methods described in 3.2 can also be used for surface preparation. An effective method for concrete removal, however, may not be effective or appropriate for a specific surface preparation requirement. For example, some concrete removal methods leave the concrete surface too rough or irregular for the intended repair material

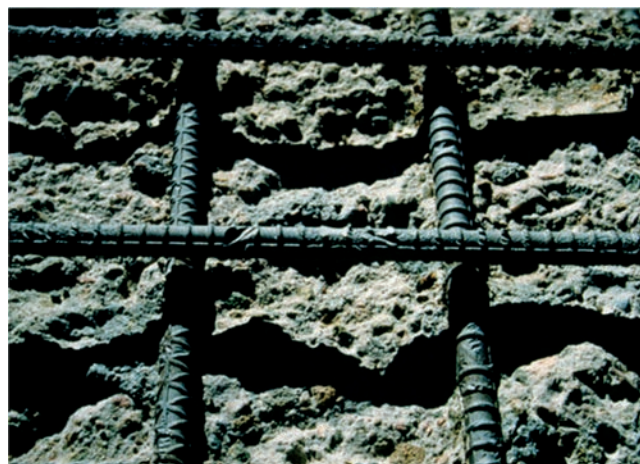


Fig. 3.3.1—Concrete surface profile.

such as membrane coatings. In these cases, removal methods specifically intended for the final surface preparation may be required. **ICRI 310.2R** provides a concrete surface profile (CSP) system for determining the surface profile necessary for various repair applications (Fig. 3.3.1). Sandpaper grit size is also commonly used as a means to characterize surface profile (**ASTM D7682**).

Some concrete removal methods damage or weaken the remaining concrete surface. This may be critical if structural bonding of the repair material is important. For example, microcracking of the concrete surface occurs when using certain removal methods. Left in place, microcracking often produces a weakened plane in the underlying concrete substrate, below the bond line. In this case, a less invasive and aggressive method of final surface preparation, such as abrasive or water blasting, may be necessary to remove the damaged surface layer.

In many repair situations, the proposed repair requires only surface profiling, exposure of coarse or fine aggregate, removal of a thin layer of damaged concrete, or cleaning of the concrete surface. Within the limits described in the previous paragraph, several of the concrete removal methods described in 3.2 can be used for this type of surface preparation. The referenced methods offer a wide range of surface characteristics and results. For example, the required surface preparation may vary from a light abrasive cleaning suitable for the application of a coating, to a deeper roughening and surface profiling necessary for good bond and reliable performance of the repair material. Selecting a suitable method of surface preparation is extremely important, as it influences the cost and performance of the repair.

3.3.2 Surface preparation methods—Common surface preparation techniques include abrasive blasting, shot-blasting, waterblasting, and cleaning methods. Table 3.3.2 provides a general description of surface preparation techniques. Refer to **ICRI 310.2R** for additional information on these methods.

3.3.2.1 Abrasive blasting—Abrasive blasting removes and cleans concrete by propelling an abrasive medium in compressed air or high-pressure water at high velocity

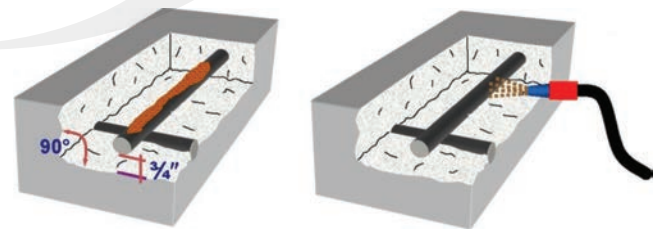
Table 3.3.2—Summary of features and considerations/limitations for surface preparation methods

Category	Features	Considerations/limitations
Abrasive blasting— Sandblasting (dry/wet) (uses equipment that propels an abrasive medium at high velocity at the concrete to abrade the surface)	a) Efficient method for roughening the surface and exposing aggregate b) Cleans reinforcing steel c) Removes surface contamination	a) Dry sandblasting procedure produces large volumes of dust b) Wet sandblasting is slow
Low-pressure water blasting (with abrasives)	a) Selectively removes defective concrete b) Precise control of removal process c) Cleans reinforcing steel while removing concrete d) Produces minimal damage to remaining concrete e) Produces no heat or dust f) Abrasives enable jet to cut steel reinforcement and hard aggregates	a) High initial investment b) Additional protection and safety procedures may be required due to water pressure c) Controlling flow of contaminated waste water may be required
Abrasive blasting—Shotblasting	a) Efficient method for roughening the surface and exposing aggregate b) Low dust emissions c) Removes surface contaminants d) Controlled depth of concrete removal e) Readily available commercially	a) Large units may produce high noise levels b) High voltage power requirements
Chemical cleaning	a) Application of chemicals to remove dirt and contaminants from surface b) Additional surface preparation may be necessary to remove cleaning chemical residue c) Follow cleaning chemical manufacturer's recommendations d) Follow coating manufacturer's instructions	a) Additional surface preparation may be necessary b) May not be effective in removing all contaminants c) May have strong chemical odor d) Protection of adjacent area necessary
Acid etching	a) Effective in removing cement-based materials b) Increases porosity of concrete surface	a) Protective clothing is necessary b) Large amounts of water necessary c) May permanently stain concrete d) Protection of adjacent area necessary e) May contaminate and damage remaining concrete surface
Low-pressure water cleaning (without abrasives)	a) Effectively removes surface contaminants without chemical residue b) Minimal protection of adjacent areas necessary	a) Control of large amounts of water b) Removal of small amounts of concrete may be noticeable

against the concrete surface to abrade and pulverize it. Abrasive blasting is commonly used to clean reinforcing steel and clean and profile concrete surfaces in preparation for sealers, coatings, and overlays. The method can also remove surface contaminants, brittle coatings, and adhesive films. The method can be used on horizontal, vertical, and overhead surfaces. Depth of concrete removal depends on the duration of the blasting as well as the size and cutting efficiency of the abrasive medium. Commonly used methods include sandblasting, shotblasting, and high-pressure water blasting.

3.3.2.1.1 Sandblasting—Sandblasting is the most commonly used abrasive blasting method in the construction industry (Fig. 3.3.2.1.1). The process uses common sands, silica sands, metallic sands, granular slags, or other media for the abrasive medium. The process may be executed by three techniques (3.3.2.1.1.1 through 3.3.2.1.1.3).

3.3.2.1.1.1 Dry sandblasting—In dry sandblasting, abrasive particles are propelled at concrete and steel surfaces in a stream of compressed air at a minimum pressure of 100 psi (0.7 MPa). The compressor size will vary depending on the size of the sandblasting pot. The abrasive particles are typically angular and may range in size from passing a No. 70 to a No. 4 (212 to 4.75 mm) sieve. The rougher the required surface condition, the larger the abrasive particle size necessary. Finer sands are used for removing contaminants

**Fig. 3.3.2.1.1—Sandblasting.**

and laitance from the concrete and loose scale from reinforcing steel. Coarser sands are commonly used to expose fine and coarse aggregates in the concrete by removing the paste or tightly bonded corrosion products from reinforcing steel. Although abrasive blasting has the ability to remove concrete, it is not economically practical to remove more than 0.25 in. (6 mm) from the concrete surface. Dry abrasive blasting will produce large quantities of airborne particulates, such as dust, and precautions should be taken to protect personnel and equipment in the work area.

3.3.2.1.1.2 Wet sandblasting—In wet sandblasting, the free particulate rebound that results from the sand being projected at the concrete surface is confined within a circle of water. Although this process reduces the amount of airborne partic-



Fig. 3.3.2.1.2—Shotblasting.

ulates, some of the water intercepts the sand being projected at the concrete surface and reduces the efficiency of the abrasive blasting operation to effectively remove concrete and provide surface profile. This process is generally limited to cleaning a concrete surface or reinforcing steel.

3.3.2.1.1.3 Low-pressure water blasting with abrasives—Low-pressure water blasting with abrasives is a cleaning system using a stream of water at low pressure (1500 to 5000 psi [10 to 35 MPa]) with an abrasive such as sand, aluminum oxide, or garnet, introduced into the stream. This equipment can remove dirt or other foreign particles and concrete laitance, thereby exposing the fine aggregate and leaving the concrete surface clean and free of dust.

This method eliminates airborne particles that normally occur when using dry/wet abrasive blasting procedures. The water used is collected and the abrasive removed before the water is discharged into a wastewater system.

3.3.2.1.2 Shotblasting—Shotblasting equipment cleans and removes concrete by projecting steel shot at the concrete surface at high velocity within an enclosed blast chamber that recovers and separates most of the dust and reusable shot (Fig. 3.3.2.1.2). The shot erodes and pulverizes the concrete at the surface. The depth of removal is controlled by shot size, machine setup, and rate of travel. The shot rebounds with the pulverized concrete and is vacuumed into the body of the shotblasting machine. The concrete particulates are separated out and deposited into a holding container to be discarded later while the shot is reused. The shotblasting process is a self-contained operation that is highly efficient and environmentally sound.

Shotblasting uses shot of varying sizes. The final surface profile required determines the size of the shot and the speed at which the machine will travel. A surface cleaning operation is achieved by using smaller (0.017 to 0.028 in. [0.43 to 0.71 mm] diameter) shot and setting the machine for maximum travel speed. Concrete removal up to 1/4 in. (6 mm) is possible in a single pass by increasing the size of the shot (0.033 to 0.055 in. [0.84 to 1.4 mm] diameter) and reducing the travel speed. Shotblasting can provide CSP ranging from CSP2 to CSP8 (ICRI 310.2R), making

this method suitable for roughening horizontal surfaces in preparation for receiving sealers, coatings, and overlays. It is also useful for removing existing coatings, adhesives, and surface contaminants. Hand-held equipment is also available for use on vertical surfaces.

3.3.2.2 Cleaning methods—Common methods of cleaning concrete surfaces are discussed in the following.

3.3.2.2.1 Chemical cleaning—In many cases, chemical cleaning methods of surface preparation are not appropriate for use with the concrete repair materials and methods presented in this guide. With certain sealers and coatings under certain conditions, however, it may be possible to use detergents, trisodium phosphate, and various proprietary concrete cleaners to remove dirt, oil, grease, buildup, and oxidation deposits from concrete surfaces (ASTM D4258). All traces of the cleaning agent should be removed after the contaminating material is removed. Solvents should not be used to clean concrete because they may dissolve the contaminant and carry it deeper into the concrete.

3.3.2.2.2 Acid etching (ASTM D4259 and D4260)—Acid etching of concrete surfaces has long been used to remove laitance and surface concrete. The acid removes cement paste and provides a slight surface profile by exposing fine aggregate. This lightly profiled surface promotes penetration and adhesion of sealers and coatings, especially thin-film coatings. Acid should only be used when no alternative means of surface preparation can be used. ACI 503R does not recommend the use of acid etching. Acids may penetrate the concrete surface through cracks and promote corrosion of underlying reinforcing steel in structural concrete. The acids can weaken the remaining cement paste on the concrete surface. Care should be taken to neutralize residual acid on prepared surfaces (ASTM D4262) and in wastewater. Thorough removal of etching debris is required to eliminate bond-inhibiting contaminants on the concrete surface. As such, large quantities of rinse water, mechanical scrubbing, and vacuum removal are necessary.

3.3.2.2.3 Low-pressure water cleaning without abrasives—Water is sprayed to remove dirt and loose, friable material. Using pressures less than 5000 psi (35 MPa), this method does not remove any significant amount of concrete. It can be used outdoors or indoors where mist and water can be tolerated. This method can be used in horizontal, vertical, or overhead situations. However, it generally does not produce any significant increase in texture, profile, or pattern in the concrete and therefore should be a supplement to other methods in most surface preparation applications (ICRI 310.2R).

3.3.3 Cleaning reinforcing steel—All exposed surfaces of the reinforcement should be thoroughly cleaned of all loose concrete, rust, oil, and other contaminants. Sandblasting is the preferred method. The degree of cleaning depends on the repair procedure and material selected. For limited areas, wire brushing or other hand methods of cleaning may be acceptable. When cleaning the steel and removing loose particles from the repair area after cleaning, neither the reinforcing steel nor the concrete substrate should be contaminated with oil from the air compressor. For this reason, either

an oil-free compressor or one that has a good oil trap should be used. High-pressure water blasting is also effective in cleaning the surface and reinforcing steel. When using moisture-sensitive repair materials, it will be necessary to remove any excess water before application of repair material. Saw-cut edges of the repair area should also be abrasive-blasted to roughen the saw cut vertical surface. Refer to 5.4 for reinforcement repair and 6.7.4 and 6.7.5 for installation of embedded galvanic anodes and cathodic protection systems to reinforcing steel.

3.3.4 Final cleaning of repair area—Upon completion of surface preparation and cleaning of the reinforcing steel, the surface should be clean, dry, and free of microcracking and bruising. All loose concrete, aggregate, rust, oil, and other contaminants should be removed from the concrete surface and reinforcing steel. This may require further sand, water, or air blasting; vacuuming; or other techniques.

3.4—Quality control and assurance

Quality control and assurance procedures are required throughout the concrete removal and surface preparation operations. These can be accomplished through visual inspection, soundings, and use of a covermeter or other means to locate reinforcement. Sounding is an excellent means to identify delaminated and debonded concrete; however, identification of subsurface cracks, microcracking, and the extent of deterioration or other internal defects may not be determined by these methods alone. Other means of evaluation should be used to properly identify the extent of deteriorated and damaged concrete and to verify its complete removal in the repair process.

Various evaluation methods (ACI 228.2R and ICRI 210.4) can provide valuable information about the condition of the concrete repair before, during, and after concrete removal. Some test methods require concrete core samples from the existing concrete or repair material. More common test methods and evaluations performed during the repair process are outlined:

- 1) Methods for concrete strength
 - a) Cores and cylinders—compressive, tensile, modulus of elasticity, and splitting tensile strength
 - b) Pullout (ASTM C900)
 - c) Pulse velocity (ASTM C597)
- 2) Reinforcing steel location
 - a) Covermeter
 - b) Ground-penetrating radar (GPR)
 - c) X-ray
- 3) Delamination, debonding identification, and microcracking (can be identified by petrographic analysis)
 - a) Visual examination
 - b) Acoustic impact (ASTM D4580—includes chain drag/hammer sounding, electromechanical sounding, and rotary percussion methods)
 - c) Impact-echo (ASTM C1383)
 - d) Infrared thermography (ASTM D4788)
 - e) Ground-penetrating radar (GPR) (ASTM D6087)
- 4) Surface cleanliness and strength (ACI 515.1R)
 - a) Test for pH of cleaned surfaces (ASTM D4262)

- b) Surface cleaning concrete for coatings (ASTM D4258)
 - c) Testing by tape lift (ASTM E1216)
- 5) Measuring surface profile (ICRI 310.2R)
- a) Replica putty (ASTM D7682)
 - b) Replica tape (ASTM D4417)
 - c) Sand method (ASTM E965)
 - d) Laser profilometry
- 6) Tensile pull-off testing (ASTM C1583, ICRI 210.3)

CHAPTER 4—REPAIR MATERIALS

4.1—Introduction

This chapter describes the various categories of materials available for repair or rehabilitation of concrete structures. Typical properties, advantages, disadvantages or limitations, typical applications, and applicable standards and references are discussed for each repair material. General guidance on selecting repair materials is also provided. For more information on selecting repair materials, refer to ACI 546.3R.

4.2—Concrete replacements and overlays

To match the properties of the concrete being repaired as closely as possible, portland-cement concrete and mortar or other cementitious compositions using similar proportions of ingredients are typically the best choices for repair materials. The new cementitious repair material should be compatible with the existing concrete substrate.

4.2.1 Conventional concrete—Conventional concrete composed of portland cement, aggregates, and water is often used as a repair material. Admixtures are used to entrain air, accelerate or retard hydration, improve workability, reduce mixing water requirements, increase strength, reduce drying shrinkage, reduce the potential for corrosion of steel reinforcement, reduce expansion of alkali-aggregate reaction, or alter other properties of the concrete (ACI 212.3R). Pozzolanic materials such as fly ash, silica fume, granulated blast-furnace slag or other supplementary cementitious materials may be used in conjunction with portland cement for economy or to provide specific properties such as reduced early heat of hydration, improved later-age strength development, reduced permeability, or increased resistance to alkali-aggregate reaction and sulfate attack.

Concrete proportions should be designed to provide the workability, density, strength, and durability necessary for the particular application (ACI 211.1). To minimize shrinkage cracking, the repair concrete should have a water-cementitious materials ratio (w/cm) as low as possible and a coarse aggregate content as high as possible. When proper restraint is provided, shrinkage-compensating concrete also contributes to the reduction of drying shrinkage cracking (ACI 223R). Frost-resistant normalweight concrete should have a w/cm not exceeding 0.45 for thin sections, such as 1.5 to 3 in. (40 to 75 mm) and 0.50 for greater thicknesses (ACI 201.2R). Mixing, transporting, and placing of conventional concrete should follow the guidance given in ACI 301, ACI 304R, ACI 304.1R, ACI 304.2R, ACI 304.5R, and ACI 304.6R.



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4.2.1.1 Advantages—Conventional concrete is readily available, well understood, economical, has similar properties to the existing concrete, and is relatively easy to produce, place, finish, and cure. Generally, concrete mixtures can be proportioned to match the hardened properties of the underlying concrete, making conventional concrete applicable in a wide range of repairs.

Conventional concrete can be easily placed under water using a number of familiar techniques and precautions to ensure the integrity of the concrete after placement (ACI 304R and ACI 546.2R). Concrete is typically placed under water using a tremie or a pump.

4.2.1.2 Limitations—Conventional concrete should not be used in repairs where the aggressive environment that caused the original concrete to deteriorate has not been eliminated, unless an appropriate design mixture for the exposure condition is used or a reduced service life is acceptable. For example, if the original deterioration was caused by acid attack, aggressive water attack, or abrasion-erosion, repair with conventional concrete may not be successful unless the cause of deterioration is mitigated.

The shrinkage properties of the repair materials are critical because the new repair materials are being placed on an existing substrate that has likely undergone essentially all the shrinkage that it will experience. Curing requirements, as well as the required properties of the repair material, including strength, modulus of elasticity, and limitations on maximum shrinkage strain, if needed, should be addressed by the licensed design professional (LDP) in the repair specifications.

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

4.2.1.3 Applications—Conventional concrete is often used in repairs involving relatively thick sections and large volumes of repair material. Typically, conventional concrete is appropriate for partial- and full-depth repairs and resurfacing overlays where the minimum thickness is greater than 2 in. (50 mm), especially where the overlay extends beyond the reinforcement, or where the repair area is large. Conventional concrete is commonly used for repairs of slabs, walls, columns, piers, and hydraulic structures (McDonald 1987), as well as for full-depth repairs or overlays on bridge or parking structure decks.

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

4.2.1.4 Standards—ASTM C94 covers ready mixed concrete manufactured and delivered to a purchaser in a freshly mixed and unhardened state. Properties such as shrinkage and bond are not addressed in this specification and should be specified separately.

4.2.2 Conventional mortar—Conventional mortar is a mixture of portland cement, fine aggregate, and water.

Water-reducing admixtures, supplementary cementitious materials, expansive components, and other modifiers are often used with conventional mortar to minimize shrinkage and adjust other properties.

4.2.2.1 Advantages—The advantages of conventional mortar are similar to those of conventional concrete, except that mortar can be placed in thinner sections. A wide variety of prepackaged mortars are available. They are particularly appropriate for small repairs.

4.2.2.2 Limitations—Mortars generally exhibit increased drying shrinkage compared to concrete because of their higher water volume, higher unit cement content, higher paste-aggregate ratio, and the absence of coarse aggregate. Proper air entrainment, which is approximately 4 to 6 percent, is often required to provide adequate resistance to freezing and thawing as well as scale resistance; however, air content does reduce the strength of the mortar. Prepackaged mortars typically include air-entraining admixtures (Types IA, IIA, or IIIA).

4.2.2.3 Applications—Conventional mortar should not be used in many situations when thin repair sections are required. These applications should be reviewed when installed in the path of vehicular traffic that is subject to repetitive loading. Because field conditions affect the development of the performance of mortar, testing for relevant properties should be performed to closely simulate the application conditions.

4.2.2.4 Standards—ASTM C387 covers the production, properties, packaging, and testing of packaged, dry, combined materials for mortar and concrete. Special consideration should be given to properties not covered in this specification, such as shrinkage and durability.

4.2.3 Proprietary concrete and mortars—Proprietary repair mortars are prepackaged mortars that are a blend of portland cement or specialty cement; fine aggregate; and admixtures such as plasticizers, expansive components, densifiers, accelerators, polymers, thixotropic agents, and other additives. Depending on the specific use, mortars may contain variable aggregate gradations for different placement depths and consistencies. Proprietary repair mortars are also available that are trowelable, sprayable, and specifically intended for overhead or vertical applications. Some proprietary repair mortars can be extended with coarse aggregate for deeper application sections.

4.2.3.1 Advantages—The advantages of proprietary repair materials are convenience of use and the broad range of products with different physical and mechanical properties to meet different conditions, such as partial-depth repairs on vertical and overhead surfaces without the need of forms as well as form-and-pour applications. They often have faster set times and shorter cure times when compared with conventional concrete and mortar. They are suitable for performance-based requirements, as the composition typically is formulated to achieve published values. The preblended materials used in proprietary mortars are convenient for small quantity placements where the proportioning of conventional mortars is inconvenient; difficult; and time-consuming.

or too complex for field conditions, such as the quantity of material used, rapid hardening, or accessibility.

4.2.3.2 Limitations—Proprietary repair mortars may have different mechanical properties than the concrete being repaired. In addition, the substrate concrete has likely already experienced most of its shrinkage and property development. Because proprietary mortars may be cement-rich and use a complex blend of modifiers, they can have a propensity for high shrinkage compared with conventional concrete. Shrinkage characteristics can be provided by the material manufacturer. Although there are no industry standards specifying bond strength of these mortars, International Concrete Repair Institute (ICRI) 210.3 or ASTM C1583 tensile bond testing is appropriate for evaluating in-place bond.

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

4.2.3.4 Standards—ASTM C928, the standard specification for packaged, dry, rapid-hardening cementitious materials for concrete repairs, cautions that chloride levels greater than 1 lb/yd³ (600 g/m³) of the hardened repair material is indicative that the packaged material contains sufficient chlorides to cause corrosion-to-steel reinforcement when the concrete is exposed to weather, is on the ground, or is in a moist environment (ACI 222R). Much lower chloride ion content should be used in prestressed concrete. The allowable drying shrinkage is up to 0.15 percent at 28 days according to ASTM C157, although this much shrinkage or additional drying shrinkage will likely compromise the integrity of the repair. This standard is not all-inclusive, and compliance to ASTM C928 is no assurance of the required suitability or durability of the repair material. The U.S. Army Corps of Engineers (USACE) UFGS-03 01 32 guide specifications (USACE 2009) limit unrestrained drying shrinkage to 0.04 and 0.10 percent at 28 days and ultimate, respectively, for repair of civil works-type structures. Limits on restrained shrinkage are also specified. ICRI 320.3R and ACI 364.3R provide guidance for appropriate tests to determine properties and describe characteristics of proprietary repair mortars. Information on criteria for selecting proprietary repair mortars can be found in ACI 546.3R.

4.2.4 Cement grouts—Cement grouts are commonly mixtures of hydraulic cement, fine aggregates, and water that produce a plastic, flowable or fluid consistency grout. Some grout formulations do not include all of these components or provide alternate components to achieve the same type of final consistency, workability, and strength. Admixtures are frequently included in the grout to reduce segregation of the contents, reduce mixing water, accelerate or retard time of setting, minimize shrinkage, reduce or eliminate bleed, improve pumpability or workability, or improve the durability of the grout. Fly ash may be used to enhance perfor-

mance or reduce cost. Silica fume may be used to increase chemical resistance, density, durability, and strength while decreasing permeability. Prepackaged grout compliant with ASTM C1107 may not be appropriate for some types of repairs that do not provide restraint or provide proper curing and should never be modified without the manufacturer's approval.

4.2.4.1 Advantages—Cement grouts are economical, readily available, easy to install, and closely compatible with concrete. Admixtures can modify cement grouts to meet specific job requirements. Shrinkage-reducing admixtures and expansive components are available to minimize shrinkage effects. Non-shrink grouts are also available.

4.2.4.2 Limitations—Cement grouts can be used for repairs by injection, but only where the width of the opening is sufficient to accept the solid particles suspended in the grout. The minimum crack width at the point of introduction should be approximately 0.25 in. (6 mm).

4.2.4.3 Applications—Typical applications of hydraulic-cement grout may vary from grout slurries for bonding old concrete to new concrete, to filling of large dormant cracks, or to filling of voids around or under a concrete structure. Non-shrink cement grouts can be used to repair spalled or honeycombed concrete or to install anchor bolts in hardened concrete, but should be used in accordance with the manufacturer's instructions.

4.2.4.4 Standards—The U.S. Army Corps of Engineers CRD C621-93 (USACE 1993) covers three grades of packaged, dry, hydraulic-cement grouts (non-shrink) intended for use under applied load, such as to support a structure or a machine, where shrinkage is to be minimized.

4.2.5 Polymer-portland-cement concrete and mortar—Polymer-portland-cement concrete and mortar (PPCC) and latex-modified concrete (LMC) are identified as portland cement and aggregate combined, at the time of mixing, with organic polymers dispersed or redispersed in water. This dispersion is called a latex, where the organic polymer is a substance composed of thousands of simple molecules combined into large molecules. The simple molecules are known as monomers, and the reaction that combines them is called polymerization. The polymer may be a homopolymer if it is made by the polymerization of one monomer, or a copolymer if two or more monomers are polymerized.

Polymer dispersions are added to the concrete mixture to improve the properties of the final product. These properties include improved bond strength to concrete substrates, increased flexibility and impact resistance, improved resistance to penetration by water and by dissolved salts, and improved resistance to freezing and thawing.

Of the wide variety of polymers investigated for use in PPCC, polymers made by emulsion polymerization have been the most widely used and accepted (ACI 548.3R). Styrene butadiene and acrylic latexes have been the most effective and predictable for concrete restoration. Other commonly used latexes include polymers and copolymers of vinyl acetate with ethylene (VAE) or other vinyl monomers such as vinyl versatate.



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When emulsified and mixed with concrete, epoxies provide excellent resistance to freezing and thawing, reduced permeability, and improved chemical resistance. The bond of epoxies is excellent whereas flexural, compressive, and tensile strengths can be high. Epoxy emulsions, however, have had limited use in concrete due to the desire to use repair materials with physical properties similar to the substrate.

Mixture proportions depend on the specific application and the type of polymer used in the PPCC. Levels of 10 to 20 percent polymer solids by mass of cement are required for most applications. Typical *w/cm* for workable PPCC mixtures used for repair range from 0.30 to 0.40 for mixtures containing latexes, and 0.25 to 0.35 for mixtures containing epoxies (ACI 548.1R). While latex polymers are used almost exclusively for PPCC overlays, redispersible polymer powders have been used as well. However, these polymer powders are used more commonly in repair situations.

4.2.5.1 Advantages—Polymer-portland cement concrete overlays have exhibited excellent long-term performance. Properly installed overlays are highly resistant to freezing-and-thawing damage, and they exhibit minimal bond failure after many years of service. Latex-modified concrete overlays installed on severely deteriorated bridge decks after proper surface preparation continue to perform many years after installation. Reports of satisfactory long-term performance on structures of variable initial condition and harsh in-service exposure are common (Virginia Transportation Research Council 2001).

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

Styrene-butadiene PPCC has excellent durability for exterior exposures or environments where moisture is present.

4.2.5.2 Limitations—Polymer-portland-cement concrete should be placed and cured at 45 to 85°F (7 to 30°C) with special precautions taken when either extreme is reached (ACI 548.1R; ACI 306.1).

Handling and finishing PPCC is limited to less than 30 minutes; therefore, mobile volumetric mixers fitted with an additional storage tank for the latex should be used for large applications of LMC. When small batches are mixed in drum or mortar mixers, the mixing time should be limited to 3 minutes. Longer mixing times result in an increase in total air content with subsequent reductions in compressive strength. Latex-modified concrete has a tendency for plastic shrinkage cracking during field placement. Special precautions are necessary when the evaporation rate exceeds 0.1 lb/ft²/h (0.5 kg/m²/h) (ACI 308R; ACI 548.4).

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

Polyvinyl acetate should not be used in applications that may be exposed to moisture.

Epoxy emulsions are more expensive than most latexes, and some are susceptible to color change and deterioration from exposure to sunlight. Surface discoloration occurs

when the concrete is exposed to UV light. Where such discoloration is not acceptable, acrylic polymers should be used.

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

Polymer-portland-cement concrete is most commonly used for overlays and is normally applied in sections ranging from 1.5 to 4 in. (40 to 100 mm) thick for concrete and 0.75 to 1.5 in. (20 to 40 mm) for mortars. These systems restore lost sections and provide a new high-strength wearing surface that is very durable against weathering and can be placed into service when it has developed sufficient strength, which is dependent upon the hydration of the cement.

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

4.2.5.4 Standards—ASTM C685 covers concrete made from materials continuously batched by volume and mixed in a volumetric mixer. Tests and criteria for batching accuracy and mixing efficiency are specified. ACI 548.4 covers the placement of styrene-butadiene LMC overlays for bridge decks. ASTM C1438 covers latex and redispersible polymer powder modifiers, and ASTM C1439 covers test methods for PPCC. ACI 548.1R includes a bibliography of major references covering polymers in concrete and a glossary of terms.

4.2.6 Polymer concrete and mortar—Polymer concrete and mortar (PC) is a composite material in which the aggregate is bound together in a dense matrix with a polymer binder. The composites do not contain a hydrated cement phase, although portland cement can be used as an aggregate or filler. The term “PC” should never suggest a single product but rather a family of products. Use of the term “PC” in this section also includes mortar.

Polymer concrete and mortar has been made with a variety of resins and monomers, including polyester, epoxy, furan, vinylester, high-molecular-weight methacrylates (HMWM), and styrene (ACI 548.1R). Polyester resins are desirable because of moderate cost, availability of a great variety of formulations, and relatively good PC properties. Furan resins are low cost and highly resistant to chemical attack. Epoxy resins are generally higher in cost, but may offer advantages such as low shrinkage, and some formulations bond to damp surfaces without requiring a primer. ACI 503R provides information on the use of epoxy compounds with concrete. A special form of PC is sulfur concrete, which is placed hot and is thermoplastic. For further information, refer to ACI 548.2R.

The properties of PC depend on the properties and the amount of the polymer used, modified somewhat by the effects of the aggregate and the filler materials. Typically, PC mixtures exhibit rapid curing; high tensile and compressive strengths; good adhesion to most surfaces; good

resistance to freezing and thawing; low permeability to water and aggressive solutions; and good chemical resistance.

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

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

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

Polymer mortars are ideally suited for thin repairs and overlays less than 0.75 in. (20 mm).

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

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

The coefficients of thermal expansion of polymer materials vary from one product to another and are higher than conventional concrete.

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

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

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

High temperatures can adversely affect the physical properties of certain PC, causing softening. Service temperatures should be evaluated before selecting PC systems for such use. Epoxy systems may burn in fires where temperatures exceed 450°F (230°C) and can soften at lower temperatures. Users of PC should consider its lack of fire resistance.

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

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

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

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

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

For exterior applications, PCs using a preplaced aggregate procedure have been successfully used in large volumes with cross sections greater than 1 ft² (0.1 m²) and greater than 15 ft (4.5 m) in length (*Project Profile 1993*).

4.2.6.4 Standards—*ACI 503.4* is a specification for repair of defects in hardened PCC with a sand-filled mortar using an adhesive binder as defined in *ASTM C881*. It includes requirements for adhesive labeling, storage, handling, mixing and application, surface evaluation and preparation, and inspection and quality control.

ASTM C881 covers two-component, epoxy-resin bonding systems for application to PCC, which are able to cure under humid conditions and bond to damp surfaces.

4.2.7 Magnesium phosphate concrete and mortar—Magnesium phosphate concrete and mortar (MPC) is based on a hydraulic cement system that is different from portland cement. Unlike portland cement and some polymer-cement concrete, which require moist curing for optimum property development, these systems produce their best properties upon air curing, similar to epoxy concrete. Rapid strength development and heat are produced, although retarded versions are available that produce less heat. These materials have been used in repairs to concrete since the mid-1970s.

4.2.7.1 Advantages—Magnesium phosphate concrete and mortar is typically classified as ultra-rapid hardening (Type URH) cement. This classification requires a minimum compressive strength of 3000 psi (21 MPa) at 1.5 hours and a maximum 28-day drying shrinkage of 0.07 percent (*ASTM C1600*). Retarded versions with extended setting times of 45 to 60 minutes at room temperature are also available. Scaling resistance is similar to air-entrained, portland-cement-based concrete materials. When extended with aggregates, abrasion resistance of MPC is similar to conventional concrete of similar strength when tested in accordance with *ASTM C672*. Neat magnesium phosphate cement naturally has lower abrasion resistance similar to portland-cement mortar of equal strength.

Magnesium phosphate mortar and concrete can be placed at temperatures as low as 32°F (0°C), or lower if the mixing water and material are heated. Magnesium phosphate mortars typically achieve 6000 psi (40 MPa) compressive strength within 48 hours and do not increase much beyond