Concrete Repair Guide

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This document provides guidance on the selection and application of materials and methods for the repair, protection, and strengthening of concrete structures. An overview of materials and methods is presented as a guide for making a selection for a particular application. References are provided for obtaining in-depth information on the selected materials or methods.

Keywords: Anchorage, cementitious, coatings, concrete, concrete removal, joint sealants, materials, placement, polymer, protection, reinforcement, repair, strengthening surface preparation, surface treatments

CONTENTS

CHAPTER 1—INTRODUCTION

1.1—Use of this document

The objective of this guide is to provide guidance on the selection and application of materials and methods for the repair, protection, and strengthening of concrete structures. The information presented is applicable to repairing damaged or deteriorated concrete structures, to overcoming design or construction deficiencies, or to adapting a structure for new uses beyond the usual design. This guide is intended as a starting point for information regarding these topics. Many of the topics covered in this guide (whether materials or methods of repair) are under the primary jurisdiction of other ACI committees. This guide presents an overview that provides enough information so that a reader can determine whether a particular material or method is suited to a particular application. After that decision is made, the reader should refer to the work of the appropriate committee for additional, in-depth information. References to the work of many other ACI committees and authors are included in this document.

1.2—Format and organization

This guide includes the following information: Chapter 2 discusses removal of existing concrete, preparation of the surface to receive repair materials, methods for repairing reinforcing and prestressing steel, and general methods for repairing concrete. Chapter 3 discusses the various types of repair materials that may be used. The reader is urged to use Chapters 2 and 3 in conjunction to select the method and material of repair for a given situation. Chapter 4 presents materials that may be used to protect concrete from deterioration. Chapter 5 covers methods for strengthening an existing structure to repair deficiencies or to carry additional loadings.

1.3—Definitions

a) Repair—To replace or correct deteriorated, damaged, or faulty materials, components, or elements of a concrete structure.

b) Repair systems—The materials and techniques used for repair.

c) Protection—The process of maintaining a concrete structure in its present or restored condition by minimizing the potential for deterioration or damage in the future.

d) Strengthening—The process of restoring the capacity of weakened components or elements to their original design capacity, or increasing the strength of components or elements of a concrete structure.

1.4—Repair methodology

A basic understanding of underlying causes of concrete deficiencies is essential to performing meaningful evaluations and successful repairs. If the cause of a deficiency is understood, it is much more likely that an appropriate repair system will be selected, and that, consequently, the repair will be successful and the maximum life of the repair will be obtained. Symptoms or observations of a deficiency must be differentiated from the actual cause of the deficiency, and it is imperative that causes and not symptoms be dealt with wherever possible or practical. For example, cracking is a symptom of distress that may have a variety of causes. Selection of the correct repair technique for cracking depends on knowing whether the cracking is due to repeated thermal cycling, accidental overloading, drying shrinkage, inadequate design or construction, or some other cause. Only after the cause or causes are known can rational decisions be made concerning the selection of a proper repair system.

1.4.1 *Evaluation*—The first step is to evaluate the current condition of the concrete structure. This evaluation may include a review of available design and construction documents, structural analysis of the structure in its deteriorated condition, review of structural instrumentation data, review of records of any previous repair work accomplished, review of maintenance records, visual examination, destructive (core drilling) and nondestructive testing, and laboratory analysis of concrete samples. Upon completion of this evaluation step, the personnel making the evaluation should have a thorough understanding of the condition of the concrete structure and may have insights into the causes of any deterioration or distress noted. Additional information on conducting surveys may be found in the reports of Committees 201, 207, and 325.

1.4.2 *Relating observations to causes*—After the evaluation of a structure has been completed, the visual observations and other supporting data are used to determine the mechanism or mechanisms that caused the problem. Since many deficiencies are caused by more than one mechanism, a basic understanding of the causes of deterioration of concrete is needed to determine what has actually happened to a particular concrete structure.

Proper evaluation of the problem is crucial and is often the deciding factor between the success or failure of a repair. Proper evaluation can never be overemphasized in developing a cost-effective repair program. Before proceeding with any remedial effort, make sure that the problems designated for repair have been properly evaluated as to the cause, effect, and degree of influence those problems have on the present and long-term serviceability and integrity of the structure. Only after the evaluation is complete can the engineer develop a suitable remedial action plan, select materials, and prepare drawings and specifications.

1.4.3 *Selecting methods and materials*—After the underlying cause or causes of the damage observed in a structure have been determined, base the selection of appropriate repair materials and methods upon the following considerations:

a) Adjustments or modifications required to remedy the cause of the deterioration if possible, such as changing the water drainage pattern, correcting differential foundation subsidence, eliminating sources of cavitation damage, providing for differential movements, or eliminating exposure to deleterious substances.

b) Constraints such as access to the structure, the operating schedule of the structure, limitations imposed by the owner of the structure, the design life of the repaired structure, and the weather.

c) Inherent problems that cannot be corrected such as continued exposure to chlorides in deicing salts or continued exposure to deleterious chemicals.

d) Environmental constraints that will play a role in the decision of methods and materials. Environmental considerations may be minimal or monumental on a repair project. Areas of concern include airborne vapors that might result from the use of certain membranes, sealers, and coatings; airborne particles resulting from abrasive blasting of silica aggregate contained in concrete; noise; and hazardous waste. These issues are governed by law, the owner, and common sense.

e) Advantages and disadvantages of making permanent versus temporary repairs. Select the materials and methods that will match the intended life of the repair.

f) Structural safety before, during, and after the repair. Repair work many times involves the removal of concrete and reinforcing steel which creates changes in the shear, bending, tensile, and compression capacity of the structure. Structural review, if necessary, should include live and dead loads and the effects of volume changes resulting from temperature changes. Areas of special concern include negative moment areas in slabs and beams, cantilever beams, joint and connection details, precast spandrel beams, and columns. Also, any requirements for temporary supports, shoring, and strengthening should be determined,

g) Available repair materials and methods and the technical feasibility of using them. When selecting the appropriate repair material, one should keep in mind that the technical data presented in manufacturer's literature may not be sufficient since the tests presented may not be representative of the use of the material under the circumstances of a particular application.

h) Capabilities of potential contractors to use specialized materials or unusual procedures successfully.

i) The most economical combination of methods and materials found to be technically feasible.

1.4.4 *Preparation of drawings and specifications*—The next step in the repair process is the preparation of project drawings and/or specifications. Since the full extent of concrete damage may not be completely known until concrete removal begins, drawings and specifications for repair projects should be prepared with as much flexibility as possible with regard to work items such as concrete removal, surface preparation, reinforcement replacement, and quantities of repair materials. A thorough condition survey, performed as close as possible to the time that repair work is executed, should help minimize variations in estimated quantities.

When existing 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 as well as adjacent areas may present unique problems during the execution of a repair project. Give special attention to shoring and bracing, particularly for slab and beam repairs, and in some cases for column repairs. Consider the redistribution of loading, especially for continuous slabs, beams, or girder systems. This factor can be especially critical during repair of unbonded prestressed structures. Provisions for these contingencies must be included in the drawings and specifications.

Effective repair specifications should be clear and concise. State the scope of the work, the materials requirements, the application considerations, and the performance testing standards with reference to specific requirements and related support documents. Detail the repair to show clearly the boundaries of concrete removal and replacement and any special features of repair system installation that are necessary. Pay special attention to the details of reinforcement repair or replacement and the preparation of existing concrete prior to surface protection system application. Contract documents should also advise the prospective contractors where information on concrete conditions that were found during any investigations can be examined for added information on the work.

1.4.5 *Selection of a contractor*—One of the most important aspects of a repair project is the selection of a qualified contractor or the preparation of a list of qualified bidders. All repair contractors are not proficient in all phases of repair work. If possible, select contractors who have shown evidence of expertise in each type of repair planned for the project.

1.4.6 *Execution of the work*—The success of a repair project will depend on the degree to which the work is executed in conformance with drawings and specifications. This is growing evidence, based on experience gained from numerous projects over several years, that concrete work on repair projects requires much greater attention to details and good practice than may be necessary for new construction. For example, many repair projects require placing relatively thin overlays, either vertically or horizontally. The potential for cracking in these placements is much greater than during placement of concrete in new construction because of the high degree of restraint. Additionally, all parties involved in a repair project must look for the unexpected—many unexpected or concealed conditions will be revealed only during the repair process.

Of all factors critical to proper repair performance, proper surface preparation cannot be overemphasized. Premature failures of repair systems are often traced to improper surface preparation. Either the engineer fails to specify correctly what is required, or the contractor fails to follow specifications or fails to use proper procedures and techniques to achieve the desired result. Removal of unsound surfaces or damaged concrete must be done properly.

1.4.7 *Quality control*—Quality control during construction is of extreme importance. Close observation of the work

is paramount as well as the implementation of an appropriate testing program. Such a program may include taking of cores for compression testing, petrographic examination, pullout testing, chloride testing, or evaluation of bond.

CHAPTER 2—CONCRETE REMOVAL, PREPARATION, AND REPAIR TECHNIQUES
2.1—Introduction and general considerations

This chapter covers removal of existing deteriorated concrete, preparation of the concrete surface to receive new material, preparation and repair of reinforcement, methods for anchoring repair materials to the existing concrete, and the various methods that are available to place repair materials. The care that is exercised during the removal and preparation phases of a repair project can be the most important factor in determining the longevity of the repair, regardless of the material or technique used.

2.2—Concrete removal

A repair or rehabilitation project will usually involve removal of deteriorated, damaged, or defective concrete. Unfortunately, there is very little guidance available to provide assistance in the selection of the best removal technique to use. In most concrete repair projects, the zones of damaged concrete are not well defined. Most references state that all damaged or deteriorated material should be removed, but it is not always easy to determine when all such material has been removed or when too much has been removed. One recommendation is to continue to remove material until aggregate particles are being broken rather than simply removed from the cement matrix. However, in some lower-strength concrete, the aggregate may not fracture.

Removal of concrete using blasting or other violent means may cause damage to the concrete that is intended to remain in place. On several rehabilitation projects where blasting was used to remove deteriorated concrete, large delaminated areas were subsequently found. These areas were relatively thin and were identified by using a hammer to take soundings. In most cases, such delaminations must be removed before repair materials are placed.

Whenever concrete is removed using impact tools, there is the potential for small-scale cracking damage to the surface of the concrete left in place. Unless this damaged layer is removed, the replacement material will suffer what appears to be a bond failure; thus, a perfectly sound and acceptable replacement material may fail due to improper surface preparation.

In all cases in which concrete has been removed from a structure by a primary means such as blasting, or impacting, the concrete left in place should also be prepared using a secondary method such as chipping, abrasive blasting or high-pressure water jetting to remove any damaged surface material.

Removal of limited areas of concrete to allow for a repair may require saw cutting of the perimeter of the removal area. This is done to provide an adequate minimum thickness of repair material at the edge of the repair (i.e. to avoid feather edges). Saw cutting may also improve the appearance of the repaired area. In some repair techniques, it may be desirable to undercut the perimeter of the repair area about 5 degrees, while for other techniques such undercutting is not desirable. Avoid concrete removal resulting in the creation of feather edge boundaries. Be extremely wary of any repair material for which claims are made that it may be feathered.

The following sections present descriptions of a number of concrete removal techniques to help in the selection process.

2.2.1 *General considerations*—Concrete removal is typically concerned with deteriorated and damaged material. However, some sound concrete may be removed to permit structural modifications. The effectiveness of various removal techniques may differ for deteriorated and for sound concrete; some techniques may be more effective in sound concrete, while others may work better for deteriorated concrete.

Select concrete removal techniques that are effective, safe, economical, and that 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 must be out of service. Some techniques will permit a significant portion of the work to be accomplished without removing the structure from service. The same removal technique may not be suited for all portions of a given structure. In some instances, a combination of removal techniques may be used to speed removal and to limit damage to the remaining concrete. Field tests of various removal techniques may be appropriate.

In general, the engineer responsible for the design of the repair should specify the result to be achieved by the concrete removal, and the repair contractor should be allowed to select the most economical removal method subject to the acceptance of the engineer. In some special circumstances, the engineer may also need to specify the removal techniques that may be used, or those which are prohibited.

The mechanical properties of the concrete to be removed provide important information required to determine the method and cost of concrete removal. Such information should be made available to contractors for bidding purposes.

2.2.2 *Monitoring removal operations*—It is essential to evaluate the removal operations to limit the extent of damage to the concrete that remains. Surface evaluation is usually accomplished by visual inspection and by sounding. However, sounding will not usually indicate near-surface microcracking or bruising. Only microscopic examination or bond testing may disclose near-surface damage.

Sub-surface evaluation may be accomplished using one of the following methods (these may be performed before, during, or after concrete removal):

a) Taking cores for visual examination, microscopic examination, compressive strength tests, and splitting tensile strength tests;

b) Pulse velocity tests;

c) Pulse echo tests.

2.2.3 *Quantity of concrete to be removed*—In most repair projects, all damaged and/or deteriorated concrete should be removed. However, estimating the quantity of concrete to be removed prior to repair is not an easy task, especially if it is intended that only unsound concrete be removed. Substantial overruns have been common. Estimating inaccuracies can be

minimized by a thorough condition survey as close as possible to the time the repair work was executed. When, by necessity, the condition survey is done far in advance of the repair work, the estimated quantities should be increased to account for any probable continued deterioration.

2.2.4 *Classification of concrete removal methods*—Removal methods may be categorized by the way in which the process acts on the concrete. These categories are blasting, cutting, impacting, milling, presplitting, and abrading. Table 2.1 provides a general description of these categories, lists the specific removal techniques within each category, and provides a summary of information on each technique. The techniques are discussed in detail in the following sections.

2.2.5 *Blasting methods*—Blasting methods generally employ rapidly expanding gas confined within a series of bore holes to produce controlled fracture and removal of the concrete. The only blasting method addressed in this report is explosive blasting.

Explosive blasting is considered to be the most cost effective and expedient means for removing large quantities of concrete. This method generally involves drilling bore holes, placing an explosive in each hole, and detonating the explosive. In order to minimize damage to the material that remains after blasting, controlled blasting techniques have been developed. 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 (usually 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.

Also used for controlled blasting are blasting machines and electrical blasting-cap delay series that employ proper timing sequences to provide greater control in reducing ground vibration. Controlled blasting has been used successfully on several repair projects. The selection of proper charge weight, bore hole diameter, and bore hole 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 dangers inherent in the handling and usage of explosives, all phases of the blasting project should be performed by qualified personnel having proven experience and ability.

2.2.6 *Cutting methods*—Cutting methods generally employ mechanical sawing, intense heat, or high-pressure water jets to cut around the perimeter of concrete sections to permit their removal. The size of the sections that are cut free is governed by the available lifting and transporting equipment. The cutting methods include diamond saw cutting, powder torch, thermal lance, powder lance, electric-arc equipment, and high-pressure water jets.

a) *High-pressure water jet (without abrasives)*—A high-pressure water jet uses a small jet of water driven at high velocities commonly producing pressures of 10,000 to 45,000 psi (69 to 310 MPa) and above. There are a number of different types of water jets that are currently being used. The most promising of these appear to be the ultra high-pressure jet and the cavitating jet. This technology is advancing rapidly and the productivity of the water jet has greatly improved over the last decade. It is now becoming competitive with some of the other cutting devices. The water jet may also be used as a primary removal method, as is described in section 2.2.9. Water jets used with abrasives are described in section 2.2.11.

b) *Saw*. Diamond or carbide saws are available in sizes ranging from very small (capable of being hand-held) to very large (capable of cutting depths of up to 52 in. [1.3 m]). A diamond saw can be used with other methods to improve crack control by making a cut through an area in which a crack plane is to be propagated.

c) *Diamond wire cutting*. Diamond wire cutting is accomplished with a wire which contains modules impregnated with diamonds. The wire is wrapped around the concrete mass to be cut and reconnected with the 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 will determine the size of the concrete structure that can be cut. This system provides an efficient method for cutting up and dismantling large or small concrete structures.

d) *Mechanical shearing*. The mechanical shearing method employs hydraulically powered jaws to cut concrete and reinforcing steel. This method is applicable for making cutouts through slabs, decks, and other thin concrete members. It is especially applicable where total demolition of the member is desired. The major limitation of this method is that cuts must be started from free edges or from holes made by hand-held breakers or other means. Care must be taken to avoid cutting into members that will support the repaired member.

e) *Stitch drilling*. The stitch drilling method employs the use of overlapping bore holes along the removal perimeter to cut out sections for removal. This method is applicable for making cutouts through concrete members where access to only one face is possible and the depth of cut is greater than can be economically cut by the diamond blade method. 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.

f) *Thermal cutting*. The powder torch, thermal lance, and powder lance employ intense heat generated by the reaction between oxygen and powdered metals to melt a slot into concrete. The applicability of these thermal devices for removing concrete from structures will mainly depend on the rate at which the resulting slag can flow from the slot. These devices employ intense heat and are especially effective for cutting reinforced

Table 2.1— Summary of features and considerations/limitations for concrete removal methods

Category	Features	Considerations/Limitations
2.2.5 Blasting Uses rapidly expanding gas confined within a series of boreholes to produce controlled fracture and removal of concrete.	Explosives Most expedient method for removing large volumes where concrete section is 10 in. (250 mm) thick or more. Produces good fragmentation of concrete debris for easy removal.	Requires highly skilled personnel for design and execution. Stringent safety regulations must be complied with regarding the transportation, storage, and use of explosives due to their inherent dangers. Blast energy must be controlled to avoid damage to surrounding improvements resulting from air blast pressure, ground vibration, and flying debris.
2.2.6 Cutting Uses perimeter cuts to remove large pieces of concrete.	High Pressure Water Jet (without abrasives) Applicable for making cutouts through slabs, decks, and other thin concrete members. Cuts irregular and curved shapes. Makes cutouts without over cutting corners. Cuts flush with intersecting surfaces. No heat, vibration, or dust is produced. Handling of debris is efficient because bulk of concrete is removed in large pieces.	Cutouts for removal limited to thin sections. Cutting is typically slower and more costly than diamond blade sawing. Moderate levels of noise may be produced. Controlling flow of waste water may be required. Additional safety precautions are required due to the high water pressure produced by the system.
2.2.6 Cutting (continued)	Diamond Saw Applicable for making cutouts through slabs, decks, and other thin concrete members. Makes precision cuts. No dust or vibration is produced. Handling of debris is efficient because bulk of concrete is removed in large pieces.	Cutouts for removal limited to thin sections. Performance is affected by type of diamonds and the diamond to metal bond in blade segments (segment selection is based upon aggregate hardness). The higher the percentage of steel reinforcement in cuts, the slower and more costly the cutting. The harder the aggregate, the slower and more costly the cutting. Controlling flow of waste water may be required.
2.2.6 Cutting (continued)	Diamond Wire Cutting Applicable for cutting large and/or thick pieces of concrete. The diamond wire chain can be infinitely long. No dust or vibration is produced. Large blocks of concrete can be easily lifted out by a crane or other mechanical methods. The cutting operation can be equally efficient in any direction.	The cutting chain must be continuous. Access to drill holes through the concrete must be available. Water must be available to the chain. Controlling the flow of waste water may be required. The harder the aggregate and/or concrete, the slower and more costly the cutting. Performance is affected by the quality, type, and number of diamonds as well as the diamond-to-metal bond in the chain.
2.2.6 Cutting (continued)	Mechanical Shearing Applicable for making cutouts through slabs, decks, and other thin concrete members. Steel reinforcement can be cut. Limited noise and vibration are produced. Handling of debris is efficient because bulk of concrete is removed in large pieces.	Limited to thin sections where an edge is available or a hole can be made to start the cut. Exposed reinforcing steel is damaged beyond reuse. Remaining concrete is damaged. Extremely rugged profile is produced at the cut edge. Ragged feather edges remain after removal.
2.2.6 Cutting (Continued)	Stitch Drilling Applicable for making cutouts through concrete members where access to only one face is feasible. Handling of debris is more efficient because bulk of concrete is removed in large pieces.	Rotary-percussion drilling is significantly more expedient and economical than diamond core drilling; however, it results in more damage to the concrete that remains, especially at the point of exit from the concrete. 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. Uncut portions between adjacent boreholes will hamper or prevent the removal. 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. Personnel must wear hearing protection due to high noise levels.

concrete; however, in general, they are considered slow and thus are not widely used.

2.2.7 *Impacting methods*—Impacting methods are the most commonly used concrete removal systems. They generally employ the repeated striking of a concrete surface with a high energy tool or a large mass to fracture and spall the concrete. The reader is cautioned that the use of these methods in partial depth removal may produce microcracking in the surface of the concrete left in place. Extensive micro-

cracking may produce a weakened plane below the bond line. The committee is currently unable to provide guidelines to prevent such damage. Where adequacy of load transfer is critical to the repair, bond testing is recommended.

a) *Hand-held breakers.* The hand-held breaker or chipping hammer is probably the best known of all concrete removal devices. Hand-held breakers are available in various sizes with different levels of energy and efficiency. The smaller hand-held breakers are commonly speci-

Table 2.1—Summary of features and considerations/limitations for concrete removal methods (cont'd)

Category	Features	Considerations/Limitations
2.2.6 Cutting (continued)	Thermal cutting Applicable for making cutouts through heavily reinforced decks, beams, walls, and other thin to medium concrete members. An effective means of cutting reinforced concrete. Cuts irregular shapes. Produces minimal noise, vibrations, and dust.	Limited availability commercially. Not applicable for cuts where slag flow is restricted. Remaining concrete has thermal damage with more extensive damage occurring around steel reinforcement. Produces smoke and fumes. Personnel must be protected from heat and hot slag produced by cutting operation.
2.2.7 Impacting Uses repeated striking of the surface with a mass to fracture and spall the concrete.	Hand-held breakers Applicable for limited volumes of concrete removal. Applicable where blow energy must be limited. Widely available commercially. Can be used in areas of limited work space. Produces relatively small and easily handled debris.	Performance is a function of concrete soundness and aggregate toughness. Significant loss of productivity occurs when breaking action is other than downward. Removal boundaries will likely require saw cutting to avoid feathered edges. Concrete that remains may be damaged (microcracking). Produces high levels of noise, dust, and vibration.
	Boom-mounted breakers Applicable for full depth removal from slabs, decks, and other thin concrete members and for surface removal from more massive concrete structures. Can be used for vertical and overhead surfaces. Widely available commercially. Produces easily handled debris.	Blow energy delivered to the concrete may have to be limited to protect the structure being repaired and the surrounding structures from damage due to high cyclic energy generated. Performance is a function of concrete soundness and aggregate toughness. Damages remaining concrete. Damages reinforcing steel. Produces feathered edges. Produces high level of noise and dust.
2.2.7 Impacting (continued)	Scabblers Low initial cost. Can be operated by unskilled labor. Can be used in areas of limited work space. Removes deteriorated concrete from wall or floor surfaces efficiently. Readily available commercially.	High cyclic energy applied to a structure will produce fractures in the remaining concrete surface area. Produces high level of noise and dust. Limited depth removal.
2.2.8 Milling Uses scarifiers to remove concrete surfaces.	Scarifier Applicable for removing deteriorated concrete surfaces from slabs, decks, and mass concrete. Boom-mounted cutters are applicable for removal from wall and ceiling surfaces. Removal profile can be controlled. Method produces relatively small and easily handled debris.	Removal is limited to concrete without steel reinforcement. Sound concrete significantly reduces the rate of removal. Can damage concrete that remains (microcracking). Noise, vibration, and dust are produced.
2.2.9 Hydrodemolition Uses high-pressure water to remove concrete	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. Does not damage the concrete that remains. Steel reinforcing is left clean and undamaged for reuse. Method produces easily handled, aggregate sized debris.	Productivity is significantly reduced when sound concrete is being removed. Removal profile will vary with changes in depth of deterioration. Method requires large source of potable water to meet water demand. Waste water may have to be controlled. An environmental impact statement may be required if waste water is to enter a waterway. Personnel must wear hearing protection due to the high level of noise produced. Flying debris is produced. Additional safety requirements are required due to the high pressures produced by these systems.

fied for use in partial removal of unsound concrete or concrete around reinforcing steel, because they do little damage to surrounding concrete. The larger breakers are used for complete removal of large volumes of concrete. Exercise care when selecting the size of breakers if breakage and secondary damage must be minimized.

b) *Boom-mounted breakers.* The boom mounted breaker is somewhat similar to the hand-held breaker except that it is mechanically operated and considerably larger. However, equipment mounted breakers differ fundamentally from hand-held pneumatic tools in that they work on the principle of very high energy and low frequency rather than low energy and very high frequency that is found in hand-held tools. The mechanical tool is normally attached to compressed air or hydraulic pressure. The reach of the hydraulic arm enables the tool to be used on walls or overhead at a considerable distance above and below the level of the machine. 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 vibrations that may damage the remaining concrete and reinforcing steel and adversely affect the integrity of the structure.

c) *Scabblers.* Scabblers are best known for their ability to remove shallow depths of concrete from a surface. The

Table 2.1— Summary of features and considerations/limitations for concrete removal methods (cont'd)

2.2.10 Presplitting	Hydraulic splitter	
Uses hydraulic jacks, water pulses, or expansive agents in a pattern of boreholes to presplit and fracture the concrete to facilitate removal.	Applicable for presplitting slabs, decks, walls, and other thin to medium concrete members.	Development of presplitting plane is significantly decreased by presence of reinforcing steel normal to presplitting plane.
Large sections can be presplit for removal, thereby making handling of debris more efficient.	Usually less costly than cutting members.	Presplit opening must be wide enough to allow cutting of steel reinforcement.
Development of presplitting plane in direction of boreholes depth is limited.	Direction of presplitting can be controlled by orientation of wedges and drill hole layout.	Secondary means of breakage may be required to complete removal.
Development of presplitting plane is significantly decreased by presence of reinforcing steel normal to presplitting plane.	Can be used in areas of limited access.	Loss of control of presplitting plane can result if boreholes are too far apart or if holes are located in severely deteriorated concrete.
Presplit opening must be wide enough to allow cutting of steel reinforcement.	Limited skills required by operator.	
Secondary means of breakage may be required to complete removal.	No vibration, noise, or fly rock is produced except by the drilling of boreholes and secondary breakage method.	
Loss of control of presplitting plane can result if boreholes are too far apart or if holes are located in severely deteriorated concrete.		
2.2.10 Presplitting (continued)	Water pulse splitter	
	Economical, portable, rugged, easy to use and maintain.	Requires boreholes at close intervals to control crack propagation.
	Devices have self-contained power sources.	Control of crack plane depth is limited.
	Negligible vibration.	Not applicable to vertical surfaces.
	Unaffected by extreme temperatures.	Produces some noise.
		Drill holes must hold water.
2.2.10 Presplitting (continued)	Expansive Agents	
	Applicable where 9 in. (230 mm) or more of a concrete face is to be removed.	Best used in gravity filled vertical or near vertical holes.
	Can be used to produce vertical splitting planes of significant depth.	Agents of putty consistency are available for use in horizontal or overhead holes.
	No vibration, noise, or flying debris is produced other than that produced by the drilling of boreholes and secondary breakage method.	Development of presplitting plane is significantly decreased by presence of reinforcing steel normal to presplitting plane.
2.2.11 Abrasive Blasting	Sandblasting	
Uses equipment that propels an abrasive medium at high velocity at the concrete to abrade the surface.	Efficient method for roughening the surface and exposing aggregate.	Dry sandblasting procedure produces large volumes of dust.
	Cleans reinforcing steel.	Wet sandblasting is slow and is difficult to operate within legal emission requirements.
	Removes surface contamination.	
	Shotblasting	
	Efficient method for roughening the surface and exposing aggregate.	Large units may produce high noise levels.
	Low dust emissions.	High voltage power requirements.
	Removes surface contaminants.	
	Controlled depth of concrete removal.	
	Readily available commercially.	
2.2.11 Abrasive blasting (continued)	High-Pressure Water Blasting (with abrasives)	
	Selectively removes defective concrete.	High initial investment.
	Removes large quantities of concrete efficiently.	Additional protection and safety procedures are required due to high water pressure.
	Precise control of removal process	Controlling flow of contaminated waste water may be required.
	Cleans reinforcing steel while removing concrete.	
	Produces minimal damage to remaining concrete.	
	Produces no heat or dust.	
	Abrasives enable jet to cut steel reinforcement and hard aggregates.	

scabbler heads are of various sizes and geometrical shapes, and varying numbers may be mounted on the cylinders. The size of the equipment depends on the number of cylinders. The equipment is normally operated by compressed air. The scabbler is designed to remove deteriorated or sound concrete from a surface to a predetermined depth.

2.2.8 *Milling methods*—Milling methods are commonly employed to remove a specified amount of concrete from large areas of horizontal or vertical surfaces. The removal depth may vary from $1/8$ in. to several in. (3 mm to approximately 100 mm). Milling operations usually leave a sound surface free of microcracks.

Scarifier. A scarifier is a concrete cutting tool that employs the rotary action and mass of its cutter bits to rout cuts into concrete surfaces. It is successfully used to re-

move loose concrete fragments (scale) from freshly blasted surfaces and to remove concrete that is cracked and weakened by an expansive agent. It is also used as the sole method of removing deteriorated and sound concrete in which some of concrete contains form ties and wire mesh. Scarifiers are available in a range of sizes. The scarifier is a very effective tool for removing deteriorated concrete on vertical and horizontal surfaces. Other advantages include well-defined limits of concrete removal, relatively small and easily-handled concrete debris, and simplicity of operation.

2.2.9 *Hydrodemolition*—High-pressure water jetting (hydrodemolition) may be used as a primary means for removal of concrete when the desires are to preserve and clean the steel reinforcement for reuse and to minimize damage to the concrete remaining in place. Hydrodemolition disintegrates

concrete, returning it to sand and gravel-sized pieces. This process works preferentially on unsound or deteriorated concrete and leaves a rough profile. Care must be taken not to punch through thin slabs or decks if unsound concrete may exist full depth in an area to be repaired.

High-pressure water jets in the 10,000 psi (70 MPa) range require 35 to 40 gal/min (130 to 150L/min). As the pressure increases to 15,000 to 20,000 psi (100 to 140 MPa) the water demand will vary from 20 to 40 gal/min (75 to 150 L/min). The equipment manufacturer should be consulted to confirm the water demand. Ultra-high-pressure equipment operating at 25,000 to 35,000 psi (170 to 240 MPa) has the capability of milling concrete to depths of $^1/_8$ in. to several inches (3 mm to approximately 50 L/min). Containment and subsequent disposal of the water are requirements of the hydrodemolition process.

Water jet lances operating at pressures of 10,000 to 20,000 psi (70 to 140 MPa) and having a water demand of 20 to 40 gal/min (75 to 150 L/min) are available. They are capable of selectively removing surface concrete in areas that are difficult to reach with larger equipment.

2.2.10 *Prospecting methods*—Presplitting methods generally employ 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 or concrete. The pattern, spacing, and depth of the bore holes affect the direction and extent of the crack planes that propagate.

a) *Hydraulic splitter*. The hydraulic splitter is a wedging device that is 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. However, secondary means of separating and handling the concrete may be required where reinforcing steel is involved.

b) Water pulse splitter. The water pressure pulse method requires that the bore holes 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 will not work if the concrete is so badly cracked or deteriorated that it will not hold water in the drill holes.

c) *Expansive agents.* Commercially available expansive agents when correctly mixed with water will undergo a large increase in volume over a short period of time. By placing the expansive agent in bore holes 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. It is best suited for use in holes of significant depth. 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.

2.2.11 *Abrading methods*—Abrading methods remove concrete by propelling an abrasive medium at high velocity against the concrete surface to abrade it. Abrasive blasting is generally used to remove surface contaminants and as a final surface preparation. Commonly used methods include sandblasting, shotblasting, and high-pressure water blasting.

a) *Sandblasting.* Sandblasting is the most commonly used method of cleaning concrete and reinforcing steel in the construction industry. The process uses common sands, silica sands, or metallic sands as the primary abrading tool. The process may be executed in one of three methods.

1) Sands are phonetically projected at the concrete or steel in the open atmosphere. The sand particles are usually angular and may range in size from passing a No. 70 to a No. 4 (212μm to a 4.75 mm) sieve. The rougher the required surface condition, the larger the sand particle size.

   The sand particles are propelled at the surface in a stream of compressed air at a minimum pressure of 125 lb/in.^{2} (860 kPa). The compressor size will vary, depending on the size of the sandblasting pot. Finer sands are used for removing contaminants 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 to remove tightly bonded corrosion products from reinforcing steel. Although sandblasting has the ability to cut quite deeply into concrete, it is not economically practical to remove more than a limited amount from the concrete surface.

2) 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 significantly reduces the amount of airborne particulates, some of the water intercepts the sand being projected at the concrete surface and reduces the efficiency of the sandblasting operation. This process is generally limited to cleaning of a concrete surface or of reinforcing steel.

3) Sand is projected at the concrete surface or the reinforcing steel in a stream of water at pressures ranging from 1500 to 3000 lb/in.^{2} (10.3 to 20.7 MPa). The water significantly reduces the efficiency of the sandblasting operation. Although this process eliminates any free airborne dust, it can only be used for cleaning concrete surfaces. The water may require treatment before being released into a storm sewer system.

b) *Shotblasting.* Shotblasting equipment cleans or removes concrete by projecting metal shot at the concrete surface at a high velocity. This equipment has the capability to remove finite amounts of sound or unsound concrete. The shot erodes the concrete from the surface. 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 condition required will determine the size of the shot required and the speed at which the machine is set to travel. A surface cleaning operation is achieved by using a small sized shot and by setting the machine for maximum travel speed. Removal of as much as 1.4 in. (6 m) in a single pass and leaving a surface with an amplitude of 1.8 in. (3 mm) can be achieved by increasing the size of the shot and by traveling at a low speed.

Shotblasting equipment has been proven to be an effective and economical method for removing up to about $^3/_4$ (199 mm) of concrete. Shotblasting had been used to remove up to 1.5 in. (38 mm) of concrete. However, the cost per unit of volume increases significantly as depth of removal increases beyond $^3/_4$ in. (19 mm).

c) *High-pressure water blasting (with abrasives).* High-pressure water blasting with abrasives is a cleaning system using a stream of water at high pressure of 1500 to 5000 psi (10 to 35 MPa) with an abrasive such as sand, aluminum oxide, or garnet introduced into the stream. This equipment has the capability of removing dirt or other foreign particles as well as concrete laitance thereby exposing the fine aggregate.

Abrasive water blasting provides a surface cleaning that eliminates the airborne particles that occur when using normal sandblasting procedures. However, the water used must be collected and the abrasive removed before the water is discharged into a storm sewer system.

Abrasive water blasting leaves the concrete surface clean and free of dust. The surface is prepared to receive the next operation such as sealer, coating, or overlay.

2.3—Surface preparation

One of the most important steps in the repair or rehabilitation of a concrete structure is the preparation of the surface to be repaired. Preparation for repair involves those steps taken after removal of deteriorated concrete. The repair will be only as good as the surface preparation, regardless of the nature, sophistication, or expense of the repair material. For reinforced concrete, repairs must include proper preparation of the reinforcing steel in order to develop a bond with the replacement concrete to insure the desired behavior in the structure. This section examines the preparation of concrete and reinforcing steel as may be required on a wide range of repair projects. If there is any doubt about the condition of concrete, it generally should be removed.

2.3.1 *General conditions*—Surface preparation consists of the final steps necessary to prepare the concrete surface to receive the repair materials. The appropriate preparation of the concrete surface depends on preceding operations and on the type of repair being undertaken.

Most of the methods described in Section 2.2 can also be used for surface preparation. However, an effective method for concrete removal may not be effective or appropriate for required surface preparation. For example, some concrete removal methods may leave the concrete surface too smooth, too rough, or too irregular for the subsequent repair. In these cases removal methods or methods specifically intended for the final surface preparation may be needed. Some concrete removal methods may damage or weaken the concrete surface. This may be critical if structural bonding of a subsequent repair is important. For example, microcracking of the concrete surface is common when impact tools are used; this may weaken the concrete surface and result in a weaker bond between the original concrete and a new concrete overlay. In this case, a less violent method of surface preparation such as sand or water may be appropriate.

In many repair situations the proposed repair may only require surface roughening, exposure of coarse or fine aggregate, removal of a thin layer of damaged concrete, or cleaning of the concrete surface. Most of the methods described in Section 2.2 can be used for this type of surface preparation, within the limits described in the proceeding paragraph. The methods offer a wide range of possible surface characteristics. For example, the finished surface may vary from that resulting from a light abrasive cleaning suitable for the application of a coating to a deeper roughening needed for strong bond and reliable performance of a critical structural repair. The choice of suitable methods is extremely important since it has a strong influence on both the cost and the performance of the repair.

2.3.2 *Methods of surface preparation*—Typical methods of surface preparation are described in the following sections:

a) *Chemical cleaning.* In most cases, chemical cleaning methods of surface preparation are not appropriate for use with the concrete repair materials and methods presented in this guide. However, with certain coatings under certain conditions, it may be possible to use detergents, trisodium phosphate, and various proprietary concrete cleaners. it is important that all traces of the cleaning agent be removed after the contaminating material is removed. Solvents should not be used to clean concrete since they will dissolve the contaminant and carry it deeper into the concrete.

b) *Acid etching.* Acid etching of concrete surfaces has long been used to remove laitance and normal amounts of dirt. The acid will remove enough cement paste to provide a roughened surface which will improve the bond of replacement materials. ACI 515.1R recommends that acid be used only when no alternative means of surface preparation can be used, and ACI 503R does not recommend the use of acid etching.

c) *Mechanical preparation.* This technique consists of mechanically removing thin layers of surface concrete using such equipment as impacting tools (breakers, scabblers), grinders, and scarifier. Depending on the equipment used, a variety of surfaces may be obtained.

d) *Abrasive preparation.* This technique consists of removing thin layers of surface concrete using abrasive equipment such as sandblasters, shotblasters, or high pressure water blasters.

2.4—Reinforcement repair

The most frequent cause of damage to reinforcing steel is corrosion. Other possible causes of damage are fire and chemical attack. The following basic preparation and repair procedures may be used for all of these causes of damage.

After the cause of the damage has been determined, it is necessary to expose the steel, evaluate its condition, and prepare the reinforcement for the repair techniques. Proper steps to prepare the reinforcement will help insure that the repair method is a long-term, rather than temporary, solution.

The most inexpensive (on a short-term basis) and common approach to repair of deterioration resulting from reinforcement corrosion is to replace concrete only where spalls or delaminations have occurred. Generally, this approach leaves chloride-contaminated concrete surrounding the repaired area which is highly conducive to corrosion. The repairs may actually aggravate corrosion in the area adjacent to them.

2.4.1 *Removal of concrete surrounding steel*—The first step in preparing reinforcing or prestressing steel for repair or cleaning is the removal of the deteriorated concrete surrounding the reinforcement. Extreme care should be exercised to insure that further damage to the reinforcing or prestressing steel is not caused by the process of removing the concrete. Impact breakers can heavily damage reinforcing or prestressing steel if the breaker is used without regard to the location of the reinforcement. For this reason, a pachometer (to determine the location and depth of the reinforcement in the concrete) and a copy of the structural drawings should be used to determine where the reinforcement is located. Once the larger areas of unsound concrete have been removed, a smaller chipping hammer should be used to remove the concrete in the vicinity of the reinforcement. Care should be taken not to vibrate the reinforcement or otherwise cause damage to its bond to concrete adjacent to the repair area.

a) *Quantity to remove.* All weak, damaged and easily removable concrete should be chipped away. If the reinforcing bars are only partially exposed after all unsound concrete is removed, it may not be necessary to remove additional concrete to expose the full circumference of the reinforcement. If during the removal process, reinforcing steel is exposed and found to have loose rust or corrosion products or is not well bonded to the surrounding concrete, then it is recommended that concrete removal should continue to create a clear space behind the reinforcing steel of $^1/_4$ in.

(6 mm) plus the dimension of the maximum size aggregate of the repair material.

b) *Inspection of reinforcing steel.* After deteriorated and sound concrete as required have been removed, reinforcing steel should be cleaned and carefully inspected to determine whether the reinforcement should be replaced. The objective of the inspection is to determine whether the reinforcing steel is capable of performing as intended by the designer. If the reinforcement has been damaged by corrosion (scaling or pitting), it may have to be replaced or supplemented and the responsible engineer should be consulted. Project specifications should include criteria whereby decisions concerning repair or replacement can be made during the project as reinforcement is exposed.

2.4.2 *Cleaning reinforcing steel*—All exposed surfaces of the reinforcement should be thoroughly cleaned of all loose mortar, rust, oil, and other contaminants. The degree of cleaning required will depend on the repair procedure and material selected. For limited areas, wire brushing or other hand methods of leaning may be acceptable. In general, sandblasting is the preferred method. When cleaning the steel and when blowing loose particles out of the patch area after cleaning, it is important that neither the reinforcing steel nor the concrete substrate be contaminated with oil from the compressor. For this reason, either an oil-free compressor or one that has a good oil trap must be used.

There is always the possibility that freshly cleaned reinforcing steel will rust between the time it is cleaned and the time that the next concrete is placed. If the rust that forms is tightly bonded to the steel such that it cannot be removed by wire brushing, there is no need to take further action. If the rust is loosely bonded so as to inhibit bond between the steel and the concrete, the reinforcing bars must be cleaned again immediately before concrete placement. If desired, a protective coating may be applied after the initial cleaning has been completed.

2.4.3 *Repair of reinforcement*—Two types of reinforcement are used in concrete structures—reinforcing steel and prestressing steel. Because of the different mechanisms by which each type performs in providing the required structural reinforcement, different repair procedures are necessary. Depending on the condition of the exposed reinforcement, a decision for a repair alternative can be made.

2.4.3.1 *Reinforcing steel*—For reinforcing steel, one or two repair alternatives may be necessary: replacement of deteriorated bars; or supplementing partially deteriorated bars. Which alternative to use is strictly an engineering decision based on the purpose of the reinforcement and the required structural capacity for the reinforced member.

a) *Replacement.* One of the methods of replacing reinforcement is to cut out the damaged area and splice in replacement bars. The length of the lap should conform to the requirements of ACI 318. If welded splices are used, welding should be performed in accordance with

ACI 318 and American Welding Society D1.4. Butt welding should be avoided due to the high degree of skill required to perform a full penetration weld since the bask side of the bars is not usually accessible. Welded splices for bars larger than No. 8 (25 mm) might present problems because the embedded bars may get hot enough to crack the surrounding concrete. Another method of splicing bars is to use mechanical connections. ACI 439.3R describes commercially-available proprietary mechanical connection devices. Mechanical connections should meet the requirements of ACI 318.

b) *Supplemental reinforcing.* This alternative is selected when the reinforcing has lost cross section, the original reinforcing was inadequate, or the existing member is to be strengthened. The decision to add supplemental reinforcing is the responsibility of the engineer. The damaged reinforcing bar should be cleaned in accordance with the guidance in Section 2.4.2. The concrete should be chipped away to allow placement of the supplemental bar beside the old bar. The length of the supplemental bar should be equal to the length of the deteriorated segment of the existing bar plus a lap splice length on each end equal to the lap splice requirements for the smaller bar diameter of the two as specified in ACI 318.

c) *Coating of reinforcing.* New and existing bars that have been cleaned for use in the repair may be coated with epoxy, latex-cement slurry, or a zinc-rich coating for protection against corrosion by chloride contamination. The coating should be applied at a thickness less than 12 mils (0.3 mm) to avoid loss of bond development at the deformations. Reinforcing bars that have lost their original deformations as a result of corrosion and cleaning will have less bond with most repair materials. Coating of these bars will further reduce the bond with repair materials.

2.4.3.2 *Prestressing steel*—Prestressing steel in structural members is of two basic types, bonded and unbonded. Deterioration or damage to the strands or bars are generally the result of impact, corrosion, or fire. Fire may anneal cold-worked, high-strength prestressing steel.

Flexibility in repair of either type is limited. Unlike mild steel reinforcing bars, the high-strength strands may need to be retensioned after repair to restore the initial structural integrity of the member. Therefore, repair options for bonded strands are different from those for the unbonded strands.

a) *Bonded strands.* Since this type of strand is bonded, it cannot be retensioned. However, a substitute strand can be provided externally. In this case the member has to be modified to provide the necessary end anchorages for the new strands. In locating the anchorages for the new strands, the engineer should avoid undesirable eccentricities. Otherwise, additional balancing strands may be required. Information on providing additional reinforcing may be found in Chapter 5.

It should be noted that in some instances of strand deterioration, the situation and the member configuration may permit only a specific repair. In such cases, repairs are developed on a case-by-case basis where general guidelines may not be applicable.

b) *Unbonded strands.* Unbonded strands are installed inside sheathings embedded in the concrete member. The strands are protected against corrosion by the sheathing or by a corrosion inhibiting material. This type of strand may usually be retensioned. Therefore, some flexibility is available to repair unbonded strands.

A deteriorated portion of a strand may be exposed by chipping the concrete and cutting the sheathing. The strand is then cut on both sides of the deterioration where sound strand is evident. Caution should be exercised when cutting tensioned strands. The removed portion of the strand is replaced with a new section which is spliced to the existing strand at the location of the cuts. The repaired strand is then restressed.

Removal of an unbonded strand from the sheathing is possible, but it is sometimes difficult. However, it is also difficult to install a replacement strand of the same diameter. When the intention is to replace a strand, it is preferable to insert a smaller diameter strand of higher strength material which would be capable of providing a stressing force comparable to that in the original strand.

2.5—Anchorage materials

There are two general categories of anchoring systems, post-installed and cast-in-place (ACI 355.1R) These are each discussed in the following sections.

2.5.1 *Post-installed anchors*—Post-installed anchor systems are those that are installed into a predrilled hole. They can be divided into two general types, bonded and expansion anchors.

Bonded anchors include both grouted (headed bolts or a variety of other shapes installed with a cementitious grout) and chemical anchors (usually threaded rods set with a two-part chemical compound that is available as glass capsules, plastic cartridges, tubes, or bulk). These anchor systems develop their holding capacities by the bonding of the adhesive to both the anchor and the concrete at the wall of the drilled hole. The different chemical systems (epoxies, polyesters, and vinyl esters) have different setting and performance characteristics that should be understood by the specifier and user.

Expansion anchor systems, sometimes called mechanical anchors, include torque-controlled, deformation-controlled, and undercut anchors. These anchors develop their strength from friction against the side of the drilled hole, from keying into a localized crushed zone of the concrete resulting from the setting operation, or from a combination of friction and keying. For the undercut anchors, strength is derived from keying into an undercut at the bottom of the drilled hole.

2.5.2 *Cast-in-place anchors*—Cast-in-place anchor systems include embedded non-adjustable anchors of various types and shapes, bolted connections, and adjustable anchors that are set in place prior to placing concrete.

2.5.3 *Anchor strength*—Anchor strength and long-term performance are dependent on a variety of factors that must

be evaluated for the specific anchor to be used. Some factors to be considered include material strength (yield and ultimate), hole diameter and drilling system used, embedment length, annular gap between the anchor and the drilled hole for post-installed anchors, concrete strength and condition, type and direction of load application (static, dynamic, tension, shear, bending, or combined loading), spacing to other anchors and edges, temperature (for chemical anchors), hole cleaning, mode of failure of the anchor system (concrete breakage, steel breakage, slip, or pullout), environmental conditions for moisture and corrosion resistance, and creep.

Site testing for verification of performance is recommended for critical applications. For chemical anchors, tests should be performed to determine the long-term creep performance at the highest expected service temperature. For all anchor systems, installation instructions should be followed to insure proper anchor performance.

2.6—Materials placement

2.6.1 *Cast-in-place concrete*—Repair by conventional concrete placement is simply the replacement of defective concrete with new concrete that is conventionally placed. This method is the most frequently used repair technique, and it is usually the most economical.

Repair by conventional concrete placement is applicable to a wide range of situations, from repair of deterioration occurring over a long time to defects caused by poor construction practices. Replacement with conventionally placed concrete should not be used in situations where an aggressive factor has caused the deterioration of the concrete being replaced. For example, if the deterioration noted has been caused by acid attack, aggressive water attack, or even abrasion-erosion, it may be expected that a repair made with conventional concrete will deteriorate again for the same reasons. However, portland cement concretes modified with silica fume, acrylics, styrene-butadiene latex, or epoxy have been successful in extending service life.

2.6.2 *Shotcrete*—Shotcrete is defined as concrete or mortar which is pneumatically conveyed at high velocity through a hose onto a surface. The high velocity of the material striking the surface provides the compactive effort necessary to consolidate the material and develop a bond to the substrate surface. The shotcrete process is capable of placing repair materials in vertical and overhead applications without the use of forms, and it can routinely place material several hundred feet from the point of delivery.

There are two basic shotcrete processes. Wet-mix shotcrete is the application process where the cement, aggregate, and water are premixed and conveyed through a hose; compressed air is added to propel the material onto the surface. Dry-mix shotcrete is the process where the cement and aggregate are premixed and pneumatically conveyed through a hose; the water is added at the nozzle as the material is projected at high velocity onto a surface.

Either method will place suitable repair materials for normal construction requirements. ACI 506R provides detailed information on the two shotcrete processes and their proper application.

In addition to placing conventional portland cement concrete and mortar, the shotcrete process is also used for placing polymer-modified portland cement concrete, fiber reinforced concretes using both steel and plastic fibers, and concrete containing silica fume and other pozzolans.

The application of repair materials by the shotcrete process should be considered wherever access to the site is difficult, where the elimination of formwork provides economy, and where significant areas of overhead or vertical repairs exist. Shotcrete is frequently used for repairing deteriorated concrete or masonry on bridge substructures, piers, sewers, dams, and building structures. It is also used for reinforcing structures by encasing additional reinforcing steel added to beams, by placing bonded structural linings on masonry walls, and by placing additional concrete cover on existing concrete structures. See Chapter 5.

The skill of the shotcrete nozzleman in applying the material generally determines the in-place quality of the repair material. ACI 506.3R provides a basis for determining the qualifications of a nozzleman. ACI 506.2 provides a basic specification for the application and inspection of concrete.

2.6.3 *Preplaced-aggregate concrete*—Preplaced-aggregate concrete is made by filling the voids in the aggregate by pumping in a cementitious or resinous grout. As the grout is pumped into the forms, it will fill the voids (displacing any water that is present), and form a concrete mass. Caution should be used to avoid the entrapment of air which will result in voids. This method is used for partial repairs or for replacement of whole members. A benefit of this method is a reduction of drying shrinkage since the aggregate particles are in point-to-point contact prior to and after grouting.

In general, the same requirements for materials and procedures that apply to preplaced aggregate concrete in new construction apply also to repair. Preplaced-aggregate concrete is covered in detail in ACI 304R and ACI 304.1R.

2.6.4 *Formed and pumped concrete and mortar*—Formed and pumped repair is a method of replacing damaged deteriorated concrete by filling a formed cavity with a repair mortar or concrete under pump pressure. This method can be used for vertical and overhead repairs. Formwork must be constructed to a strength sufficient to handle the pressure induced by hydrostatic pressure and the additional pump pressure required to consolidate the repair material. The cavity and formwork design must provide for the venting of air. Venting can be accomplished by the removal profile of the prepared concrete, by vent tubes or by drilled holes in the existing concrete. Pumping of the cavity is usually started at the lowest point in vertical repairs, or at an extremity in overhead repairs. Pumping continues until the material flows from an adjacent port in the formwork. Pumping continues until the cavity is full and the form is pressurized. During the final pressurization, the repair material is consolidated around the reinforcing steel and driven into the crevices of the prepared substrate to improve bond.

2.6.5 *Troweling and dry packing*

a)*Troweling.* Patches applied by hand troweling may frequently be used for shallow and/or limited areas of repair. These repairs may be made using portland cement mortars,

proprietary cementitious prepackaged materials, or polymer-modified grouts, or polymer grouts and mortars. Trowel applied systems are not preferred when reinforcing steel is exposed and undercut due to the difficulty of consolidation of repair material around and behind the reinforcing steel.

It is usually desirable to use the paste of the repair material as the bonding medium. The repair material must be applied to the grouted surface before the grout or paste sets. Where multiple layers are needed to build up the total thickness of the repair, the surfaces should be roughened to help in bonding subsequent layers.

The use of proprietary products should be in conformance with the manufacturer's instructions.

Successful use of trowel-applied repairs is highly dependent upon the surface preparation and the skill of the individual mason. Every effort should be made to ensure that masons are experienced, and close field observation of the work should be made. Proper troweling technique should be used to prevent the entrapment of air at the bonding surface which can cause reduced bond strength. Of particular importance is proper curing of portland cement mortars so that the patch material does not dry before hydration is complete. Special curing provisions may be advisable for repairs where accessibility is difficult.

b. *Dry packing*. Dry packing is the hand placement of a very dry portland cement mortar and the subsequent tamping or ramming of the mortar into place. Because of the low water-cement ratio, these patches, when compacted properly, can have good strength, durability, and water tightness.

Dry packing can be used for patching small areas and for filling form-tie and cone-bolt holes. Because of the labor-intensive nature of this technique, it is not often used for large repairs.

2.6.6 *Injection grouting*—Grouting is the common method for filling cracks, open joints, honeycomb, and interior voids with a hydraulic cement-based fluid suspension (cement grout) or other materials such as epoxies or urethanes (chemical grout) that will cure in place to produce a desired result. Grouting may be done to strengthen a structure, to arrest water movement, or both. Care should be taken to define the objectives of grouting and to select the proper material to meet those objectives before designing a grouting repair program. Where appropriate, quality control measures should include taking cores to verify that proper penetration and bond has been achieved.

2.6.6.1 *Cement grouting*—As used here, cement grout is defined as a mixture of cementitious material, normally portland cement based, and water, with or without fine aggregate or admixtures, proportioned to produce a pumpable consistency without excessive segregation of constituents. Grout may be injected into an opening from the surface of a structure or through holes drilled to intersect the opening in the interior.

a) *Grouting from the surface*—When grout is to be injected from the surface, short entry holes (ports), a minimum of 1 in. (25 mm) in diameter and a minimum of 2 in. (50 mm) deep, are drilled into the opening and the surface of the opening sealed between ports with a portland cement or resinous

mortar. Whether or not short pipe nipples are cemented into the holes for grout hose connections depends largely upon anticipated grouting pressures. If the ports are drilled after sealing the openings, a hand-held cone shaped fitting on the grout hose may be adequate for pressure under 50 psi (350 kPa). Where cracks or openings extend through a structure, such as a wall, the opening is usually sealed and ported on the far side as well.

Where appearance is not a factor, openings may often be sealed by caulking with cloth or fabric that will pass water or air but retain solids. Paper and materials that remain plastic are not suitable for this purpose.

The spacing of the entry ports is largely a matter of judgment based upon the nature of the work to be done. However, as a general rule, ports should be farther apart than the desired depth of grout penetration.

Prior to the start of grouting, it is advisable to flush the openings with clean water, following, to the extent possible, the procedure that will be used in grouting. Flushing is done for several reasons: 1) to wet the interior surfaces for better grout flow and penetration; 2) to check the effectiveness of the surface sealing and port system; 3) to provide information on probable grout flow patterns and internal interconnections, some possibly unexpected; and 4) to familiarize the grouting crew with the situation.

Start grouting at one end of a horizontal opening or at the bottom of a vertical opening, and continue until grout shows at the second port away from the one being pumped. Then move to the next port and continue until grout again shows at the second distant hole. Valve shut or plug each port as it is left. Follow progress on the far side of the structure, if accessible, and close ports or valves as necessary.

Grouting is usually started with a relatively thin grout, thickened as quickly as possible to the heaviest consistency that can be pumped without blockage, as determined at the grouting operation.

b) *Interior grouting*. Grouting of cracks, joints, and voids from the interior is done through 1 in. (25 mm) or larger diameter holes drilled at an angle to intersect the opening at desired depth from the surface or, as near as possible, to the bottom of the void.

Drilling is done with diamond core bits, rotary carbide bits, or percussion drills. Diamond or rotary bit drilling is preferred, especially when the openings to be grouted are relatively narrow, in order to minimize the debris that would choke the crack. Applying a vacuum to the drill stem will further reduce the possibility of drill cuttings getting into the crack. For wider openings, say $1/_2$ in. (12 mm) or more, drill cuttings are less of a problem, but in any event, all holes must be thoroughly washed and water circulated through the system before grouting.

2.6.6.2 *Chemical grouting*—Chemical grout, as defined in this guide, is any fluid material not dependent upon suspended solids for reaction. The grout should harden without adversely affecting any metals or the concrete boundaries of the opening or void into which it has been injected. From the standpoint of the user, chemical grouts are usually two component systems requiring blending at or near the point of in-

jection, or else the blending of the injected chemical with moisture or water existing in the crack or placed there by the grouter. Chemical grouts may contain various inert fillers to modify physical properties, such as consistency and heat generation, and to increase volume. Materials for chemical grouting are described in Chapter 3.

Chemical grout should be injected from the surface or the interior in the same general manner as cement grouts with the exception that, for unfilled grouts, the port sizes may be $^1/_8$ in. or $^1/_4$ in. (3 or 6 mm) in diameter and the port devices may be mechanically anchored or cemented into place.

2.6.6.3 Selection of type of grout—Factors affecting the type of grout to be selected for a given repair include:

1. Is it necessary to transmit compression, tension, shear, or a combination across the opening?

2. Is the opening active, i.e., subject to future tensile forces that may exceed the tensile or shear strength of the concrete in the vicinity of the repaired crack?

3. Is preventing water or air movement through the opening all or part of the requirement?

4. Is the width of the opening sufficient to accept the type of grout selected?

5. Does the required internal grout pressure exceed the resistance of the structure or of the surface sealer?

6. Is the rate of grout stiffening slow enough to permit the grout to reach its destination and fast enough to minimize leakage from the blind side?

7. Is the exothermal heat liberation of some chemical grouts, especially epoxy types, excessive?

8. Is the grout cost effective in relation to desired or required results?

9. Are the shrinkage, creep, and moisture absorption characteristics of the grout compatible with the project conditions?

10. Is the viscosity low enough and the pot life long enough to assure full penetration of the crack (particularly small cracks in a large concrete mass)?

a. *Cement grouts.* Cement and other grouts containing solids in suspension may be used only where the width of the opening is sufficient to accept the solid particles. For the reliable penetration of neat grouts (hydraulic cement mixed with or without pozzolans and other admixtures) mixed with approximately 10 gal of water per 100 lb (83 L to 100 kg) of solids (water-to-solids ratio of about 0.8), minimum crack width at the point of introduction should be about $^1/_8$ in. (3 mm). With flow started in the opening, such grout will penetrate through cracks 0.01 in. (0.25 mm) wide. As joint widths increase to $^1/_4$ in. (6 mm) or more, the mix water may be reduced to 5 to 6 gal per 100 lb (42 to 50 L/100 kg) of solids (water-to-solids ratio of about 0.4 to 0.5), especially when water-reducing admixtures are used. For openings of $^1/_2$ in. (12 mm) or more, and for interior voids, grouting sand or masonry sand, in an amount ranging from one to two times the mass or volume of the cementing material, may be included. Fine aggregate, meeting the requirements of ASTM C 33, may also be used when filling large voids.

Extra-finely ground speciality cements and silica fume will move into finer openings than normal hydraulic ce-

ments, but definitive information on the penetrability of these materials into cracks and joints is limited.

Hydraulic cement grouts are excellent for reintegrating and stabilizing cracked structures such as bridge piers, tunnel linings, or walls, where reestablishing compression and shear strength is the main goal. Cement grouts also provide some tensile bond, but tensile strength is difficult to predict. Expansive cement grouts are widely used to prevent water movement.

b. *Chemical grout.* Chemical grouts should be considered under two categories according to whether they harden to a rigid condition or to a flexible gel or foam. Epoxies and acrylates are examples of rigid types; polyurethane is an example of a gel.

Rigid chemical grouts bond exceedingly well to dry substrate and some will bond to wet concrete. These grouts can prevent all movement at an opening and restore the full strength of a cracked concrete member. However, if tensile or shear stresses exceeding the capability of the concrete recur after grouting, new cracks will appear in the concrete near, but generally not at the grouted crack. Rigid grouts have been observed to penetrate cracks somewhat finer than 0.002 in. (0.05 mm), the penetration being dependent on viscosity, injection pressure, temperature, and grout set time.

The principal use for gel-type chemical grouts is to shut off or greatly reduce water movement. Gel grouts will not restore strength to a structure, but they generally will maintain water tightness despite minimal movement across a crack. Most gel grouts are water solutions and will, therefore, exhibit shrinkage if allowed to dry, but they will recover when rewetted. Some gel grouts can be formulated at consistencies so near that of water that they can be injected into any opening through which water will flow. Others can be made to yield a foam that can be used in openings several inches (approximately 100 mm) wide.

2.6.7—*Underwater placement*—Placing concrete directly under water by means of a tremie or pump is a frequently used repair method. In general, the same requirements for material and procedures that apply to new construction also apply to repair placements under water. Placing concrete under water by tremie and by pump is covered in detail in ACI 304R.

Preplaced-aggregate concrete is frequently used on underwater repair projects. The concrete mortar is pumped from the bottom of the placement, displacing the water as it rises. The use of preplaced-aggregate concrete is covered in ACI 304.1R.

2.7—Bonding methods

Repair materials may or may not require a separate bonding agent. In either case the success of the repair depends upon achieving intimate and continuous contact between the repair material and the substrate. Intimate contact can be achieved by vibration, pneumatic application, high fluidity, and troweling pressure.

In cases where a separate bonding agent is to be used, application of the bonding agent to the prepared substrate must be done with care and must be timed to the placement of the repair material. Bonding agents applied to substrates may begin to set or cure prematurely creating a bond breaker with the new repair material. Cement based bonding agents are

typically sprayed or broomed, epoxy and latex based systems are rolled, broomed, or sprayed.

Whether the repair material is self bonding or a separate bonding agent is used, tests should be conducted to assure that bonding is taking place. In situ testing provides the best method to assure bonding is adequate. In situ testing of bond provides for evaluation of surface preparation, bonding, and repair material placement.

CHAPTER 3—REPAIR MATERIALS
3.1—Introduction

This chapter contains descriptions of the various categories of materials that are available for repair or rehabilitation of concrete structures. Typical properties, advantages, disadvantages or limitations, typical applications, and applicable standards will be discussed for each repair material. Also, general guidance on selection of repair materials is provided.

3.2—Cementitious materials

In order to match the properties of the concrete being repaired as closely as possible, portland cement concrete and mortar or other cementitious compositions are frequently the best choices for repair materials.

3.2.1 *Conventional concrete*—Conventional concrete is composed of portland cement, aggregates, and water. Admixtures are frequently used to entrain air, accelerate or retard hydration, improve workability, reduce mixing water requirements, increase strength, or alter other properties of the concrete. Pozzolanic materials, such as fly ash or silica fume, 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, or increased resistance to alkali-aggregate reaction and sulfate attack.

Concrete proportions must be selected to provide workability, density, strength, and durability necessary for the particular application (ACI 211.1). To minimize shrinkage cracking, the repair concrete should have a water-cement ratio as low as possible and a coarse aggregate content as high as possible. According to ACI 201.2R, frost-resistant regular weight concrete should have a water-cement ratio not to exceed 0.45 for thin sections and 0.50 for all other structures. Mixing, transporting, and placing of conventional concrete should follow the guidance given in ACI 304R.

a. *Advantages.* Conventional concrete is readily available, well understood, economical, and relatively easy to produce, place, finish, and cure. Generally, concrete mixtures can be proportioned to match the properties of the underlying concrete; therefore, conventional concrete is applicable to a wide range of repairs.

Conventional concrete can be easily placed underwater using a number of well recognized techniques and precautions to ensure the integrity of the concrete in place (ACI 304R). Concrete is typically placed underwater using a tremie or a pump.

b. *Limitations.* Conventional concrete without admixtures should not be used in repairs where the aggressive environment that caused the original concrete to deteriorate has not been eliminated unless a reduced service life is acceptable.

For example, if the original deterioration was caused by acid attack, aggressive water attack, or even abrasion-erosion, repair with conventional concrete may not be successful unless the cause of deterioration is removed.

When used as a bonded overlay, the shrinkage properties of the repair material are critical since the new material is being placed on a material that has exhibited essentially all of the shrinkage that it will experience. Full consideration of the shrinkage properties and the curing procedure should be addressed in the specification for the repair procedure.

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

c. *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 about 4 in. (100 mm) or the overlay extends beyond the reinforcement. Conventional concrete is most commonly used for repairs on walls, piers, and hydraulic structures (McDonald, 1987).

Conventional concrete is particularly suitable for repairs in marine environments because the typically high humidity in such environments minimizes the potential for shrinkage.

d. *Standards.* ASTM C 94 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 included in this specification, and they must be specified separately if they merit special consideration in a given repair.

3.2.2 *Conventional mortar*—Conventional mortar is a mixture of portland cement, fine aggregate, and water. Water-reducing admixtures, expansive agents, and other modifiers are often used with conventional mortar to minimize shrinkage.

a. *Advantages.* The advantages of conventional mortar are similar to those of conventional concrete. In addition, mortar can be placed in thinner sections. A wide variety of prepackaged mortars is available. They are particularly appropriate for small repairs.

b. *Limitations.* Mortars generally exhibit increased drying shrinkage compared to concrete because of their higher water volume, higher unit cement content, and higher paste-aggregate ratio.

High air contents are often required to provide adequate freeze-thaw durability and salt scale resistance; however, high air content does reduce strength.

c. *Applications.* Conventional mortar can be used in the same situations as conventional concrete wherever thin repair sections are required.

d. *Standards.* ASTM C 387 covers the production, properties, packaging, and testing of packaged, dry, combined materials for concrete and mortars. Special consideration should be given to properties not covered in this specification which are important in repair materials such as shrinkage and durability.

3.2.3 Dry pack—Dry pack mortar may consist of one part cement, two and one-half to three parts sand, or prepackaged proprietary materials, and only enough water so the mortar will stick together when molded into a ball by slight pressure of the hands and will not exude water but will leave the hands damp. Curing is critical because of the low initial water content of dry pack mortar.

Preshrunk mortar is a low water content mortar that has been mixed and allowed to stand idle 30 to 90 minutes, depending on the temperature, prior to use. Preshrunk mortar may be used to repair areas too small for the tamping procedure. Remixing is required after the idle period.

a. *Advantages.* Because of its low water-cement ratio, dry pack exhibits very little shrinkage. Therefore, the patch remains tight and is of good quality with respect to durability, strength, and water tightness. If the patch must match the color of the surrounding concrete, a blend of gray and white portland cement may be used. Normally, about one-third white cement is adequate, but the precise proportions can only be determined by trial.

b. *Limitations.* Dry pack is not well suited for patching shallow depressions or for patching areas requiring filling behind exposed reinforcement, or for patching holes extending entirely through concrete sections. Without adequate curing, dry pack repairs are subject to failure.

c. *Applications.* Dry pack can be used for filling large or small cavities, form tie holes, or any cavity that allows for adequate compaction. Such repairs can be accomplished on vertical and overhead surfaces without forms. Dry pack can also be used for filling narrow slots cut for the repair of dormant cracks; however, it is not recommended for filling or repairing active cracks.

d. *Standards.* None.

3.2.4 Ferrocement—Ferrocement is a term used to describe a form of reinforced concrete that differs from conventional reinforced or prestressed concrete primarily by the manner in which the reinforcing elements are dispersed and arranged (ACI 549R). Ferrocement is commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small diameter wire mesh. The mesh may be made of steel or other suitable materials.

a. *Advantages.* Ferrocement has a very high tensile strength-to-weight ratio and superior cracking behavior in comparison to reinforced concrete.

b. *Applications.* Since no formwork is required, ferrocement is especially suitable for repair of structures with curved surfaces, such as shells, and free-form shapes.

c. *Limitations.* The use of ferrocement in a repair situation will simply be limited by the nature of the repair.

d. *Standards.* There are currently no standards for ferrocement. Additional information is available in ACI 549R and 549.1R.

3.2.5 Fiber-reinforced concrete—Fiber-reinforced concrete is conventional concrete with either metallic or polymeric fibers added to achieve greater resistance to plastic shrinkage and service-related cracking. In most applications, fiber reinforcing is not intended as primary reinforcement. Fiber reinforced concrete has been used for repair using conventional and shotcrete placement methods. Information on fiber-reinforced concrete or shotcrete can be obtained from ACI 544.3R, ACI 544.4R, and ACI 506.1R.

Little information is available on performance characteristics of repair systems utilizing fiber-reinforced concrete.

a. *Advantages.* The fibers are added during concrete production and are in the concrete when it is placed. These fibers can be used to provide reinforcing in thin overlays that are not thick enough to include reinforcing bars.

b. Fiber reinforced concrete has been used for overlays of concrete pavements, slope stabilization, and reinforcement of structures such as arches or domes. Reinforced concrete structures have been repaired with fiber-reinforced shotcrete. Areas subject to shock or vibration loading, where plastic shrinkage cracking is a problem, or where blast resistance is required, could benefit from the addition of fiber reinforcement.

c. *Limitations.* The addition of fibers reduces the slump and can cause workability problems for inexperienced workers. Rust stains may occur at the surface of steel fiber-reinforced concrete due to corrosion of fibers at the surface.

In patching applications, the electrical conductivity of the patch material, when using metallic fibers, could influence corrosion activity when patches are installed around previously damaged reinforcement. For other applications, a wicking effect suggests that permeability may be higher than for conventional concrete systems of equivalent thickness. Curing and protection of fiber-reinforced concrete should be similar to that for equivalent conventionally reinforced concrete.

d. *Standards.* ASTM C 1116 covers the materials proportions, batching, delivery, and testing of fiber-reinforced concrete and shotcrete.

3.2.6 Grouts—The grouts described herein are categorized as either hydraulic cement or chemical.

3.2.6.1 Cement grouts—Cement grouts are mixtures of hydraulic cement, aggregate, and admixtures that when mixed with water produce a trowellable, flowable, or pumpable consistency without segregation of the constituents. Admixtures are frequently included in the grout to accelerate, or retard time of setting, minimize shrinkage, improve pumpability or workability, or to improve the durability of the grout. Mineral fillers may be used for reasons of economy when substantial quantities of grout are required.

a. *Advantages.* Cement grouts are economical, readily available, easy to install, and compatible with concrete. Admixtures can be used to modify cement grouts to meet specific job requirements at relatively low cost. Admixtures to minimize shrinkage are available on the market.

b. *Limitations.* Cement grouts may be used for repairs by injection only where the width of the opening is sufficient to accept the solid particles suspended in the grout. Normally, the minimum crack width at the point of introduction should be about $1/8$ in. (3 mm).

c. *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. Nonshrink cement grouts may be used to repair spalled or honeycombed concrete or to install anchor bolts in hardened concrete.

d. *Standards.* ASTM C 1107 covers three grades of packaged, dry, hydraulic-cement grouts (nonshrinkable) intended for use under applied load (such as to support a structure, a machine, and the like) where change in thickness below initial placement thickness is to be avoided.

3.2.6.2 Chemical grouts—Chemical grouts consist of solutions of chemicals that react to form either a gel or a solid precipitate as opposed to cement grouts that consist of suspensions of solid particles in a fluid. The reaction in the solution may involve only the constituents of the solution, or it may include the interaction of the constituents of the solution with other substances, such as water, encountered in the use of the grout. The reaction causes a decrease in fluidity and a tendency to solidify and fill voids in the material into which the grout has been injected.

a. *Advantages.* The advantages of chemical grouts include their applicability in moist environments, their wide ranges of gel or setting time, and their low viscosities. Cracks in concrete as narrow as 0.002 in. (0.05 mm) have been filled with chemical grout.

Rigid chemical grouts, such as epoxies, exhibit excellent bond to clean, dry substrates, and some will bond to wet concrete. These grouts can restore the full strength of a cracked concrete member.

Gel-type or foam chemical grouts, such as acrylamides and polyurethanes, are particularly suited for use in control of water flow through cracks and joints. Some gel grouts can be formulated at viscosities near that of water so they can be injected into almost any opening that water will flow through.

b. *Limitations.* Chemical grouts are more expensive than cement grout. Also, a high degree of skill is needed for satisfactory use of chemical grouts.

Chemical bonding agents, such as epoxies, have relatively short pot life and working times at high ambient temperatures.

Gel grouts should not be used to restore strength to a structural member. Most gel or foam grouts are water solutions and will exhibit shrinkage if allowed to dry in service.

c. *Applications.* Repair of fine cracks, either to prevent moisture migration along the crack or to restore the integrity of a structural member, is one of the most frequent applications of chemical grout.

Some grouts, such as epoxies, are frequently used as bonding agents.

d. *Standards.* ASTM C 881 covers two component, epoxy-resin bonding systems for application to portland cement concrete, which are able to cure under humid conditions and bond to damp surfaces.

3.2.7 Low Slump Dense Concrete—Low slump dense concrete (LSDC) is a special form of conventional concrete. It generally has a moderate to high cement factor, a water-cement ratio less than 0.40, and exhibits working slumps of 2 in. (50 mm) or less. LSDC generally gains strength rapidly and is distinctive because of its high density and reduced permeability.

a. *Advantages.* Overlays of LSDC with a minimum thickness of only $1^1/_2$ in. (38 mm) have provided up to 20 years of service when properly installed. The cost of LSDC is rela-

tively low, and it can be placed using conventional equipment with slight modifications. Compared to structural grade concrete, LSDC provides reduced chloride permeability when tested according to ASTM C 1202.

b. *Limitations.* LSDC's require maximum consolidation effort to achieve optimum density, or the use of a high-range water-reducing admixture (HRWRA) to improve workability of the concrete and reduce the compaction effort needed to provide bond to the reinforcing steel and to the underlying concrete.

These low water-cement ratio concretes generally require at least 7 days of continuous moist curing to obtain adequate hydration.

LSDC permits galvanic corrosion even with a 0.32 water-cement ratio and 1-in. (25 mm) cover (Pfeifer, Landgren, and Zoob, 1987).

Drying shrinkage cracks, depending on crack width and depth, can increase chloride ion intrusion resulting in corrosion of the reinforcing steel in bridge deck overlays (Babei and Hawkins, 1987).

c. *Applications.* LSDC is frequently used as an overlay or final wearing course in a composite repair to obtain a high (acceptable) quality, abrasion resistant, and durable concrete surface.

d. *Standards.* None.

3.2.8 Magnesium phosphate concretes and mortars—Magnesium phosphate concretes and mortars (MPC) are based on a hydraulic cement system that is different from portland cement. Unlike portland and some modified portland cement concretes which require moist curing for optimum property development, these systems produce their best properties upon air curing—similar to epoxy concretes. 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-1970's.

a. *Advantages.* Setting times of 10 to 20 minutes are typically encountered at room temperatures, and early strength development of 2,000 psi (14 MPa) within 2 hours is regularly obtained. Retarded versions with extended setting times of 45 to 60 minutes at room temperature are also available. Salt-scale resistance is similar to portland cement based concrete materials. When extended with aggregates, abrasion resistance of MPC is similar to PCC. Neat magnesium phosphate cement will naturally have lower abrasion resistance, similar to portland cement mortars.

b. *Limitations.* MPC should be used only with non-calcareous aggregates, such as silica, basalt, granite, trap rock, and other hard rocks. Reaction of carbonated surfaces with the early forming phosphoric acid produces carbon dioxide (CO_2) and weakens the paste aggregate bond.

Because of their acid-base reaction, MPC must be used only on well-prepared concrete substrates that have the carbonation layer removed by mechanical or chemical means. The MPC reacts chemically with the dust of fracture or carbonated zone and can cause a reduction in bond strength at the bond interface.

Because of the small interval between initial and final setting times, MPC generally is not hard troweled.

In a hardened state, MPC generally quickly produces concrete with high strength and high modulus of elasticity. Therefore, it is not flexible and does not have the toughness that is typically found with organic modified mortars. The material is therefore susceptible to fracturing from impact loads.

With the normal setting formulations of MPC, high heat peaks are encountered. With sustained exposure to temperatures in excess of 195 ˚F (91 ˚C) in service, strength reductions can develop.

c. *Applications.* Patching applications are the most common use of MPC. It is frequently cost effective for rapid repairs where a short down time is important. The common uses are in highway, bridge deck, airport, tunnel, and industrial repairs.

Repairs in a cold-weather environment are important applications. Due to the exothermic nature of the reaction, heating of the materials and the substrates is not usually necessary unless the temperature is below freezing. MPC is useful for cold weather embedments and anchoring because of its high bond strength and low shrinkage rate.

d. *Standards.* None.

3.2.9 Preplaced-aggregate concrete—Preplaced-aggregate concrete is produced by placing coarse aggregate in a form and later injecting a portland cement-sand grout (usually with admixtures), or a resinous material to fill the voids. Preplaced-aggregate concrete differs from conventional concrete in that it contains a higher percentage of coarse aggregate. Guidance on mixing and placing preplaced-aggregate concrete is given ACI 304R and ACI 304.1R.

a. *Advantages.* Because of the point-to-point contact of the coarse aggregate, drying shrinkage of preplaced-aggregate concrete is about one-half that of conventional concrete. Because the aggregate is preplaced and the grout pumped under pressure, segregation is not a problem and virtually all substrate voids will be filled with mortar. These factors make preplaced aggregate concrete an ideal material for applications where considerable congestion of reinforcement or other embedments, or difficult access exists. The ability of the grout to displace water from the voids between aggregate particles during injection makes this material particularly suitable for underwater repairs (ACI 304R and ACI 304.1R).

In underwater construction, higher placing rates at lower cost have been achieved with preplaced-aggregate concrete compared to conventional placing methods (ACI 304R and ACI 304.1R).

b. *Limitations.* Formwork costs for preplaced-aggregate concrete are about the same as for conventional concrete, however, additional work may be required in the installation of forming because of the need to prevent leaks. Because of the relatively high water content required to yield pumpable cementitious mortars, the permeability to gas or vapor of the mortar fraction of preplaced aggregate concrete may be somewhat greater than that of normal concrete, which is an important factor to consider where it is to be used in extreme environments. Inclusion of silica fume in the grout may mitigate this limitation, but little experience or documentation exists.

Since preplaced-aggregate concrete construction is specialized, it is advisable that repairs using this material be conducted by qualified personnel experienced in this method of construction.

c. *Applications.* Typically, preplaced-aggregate concrete is used on large repair projects, particularly where underwater concrete placement is required or when conventional placing of concrete would be difficult. Typical applications have included underwater repair of stilling basins, dams, bridges, abutments, and footings. Preplaced-aggregate concrete has also been used to repair beams and columns in industrial plants, water tanks and other similar facilities, as well as caissons for underpinning existing structures.

c. *Standards.* ASTM C 937 covers fluidifier for grout used for preplaced-aggregate concrete.

ASTM C 938 describes the laboratory procedure for selecting proportions for grout mixtures required in the production of preplaced-aggregate concrete.

3.2.10 Rapid-Setting Cements—Rapid-setting cementitious materials are characterized by short setting times. Some may exhibit very rapid strength development with compressive strengths in excess of 1000 psi (6.9 MPa) within 3 hours. Type III portland cement with accelerators has been used for the patching of concrete for a long time and has been more widely used than most other materials in full depth sections (Transportation Research Board, 1977).

a. *Advantages.* Rapid-setting cements provide accelerated strength development that which allows the repair to be placed into service more quickly than conventional repair materials. This advantage is of importance in repair of highways and bridges because of the reduced protection times, lower traffic control costs, and improved safety.

b. *Limitations.* Although most rapid setting materials will be as durable as concrete, some, due to their constituents, may not perform well in a specific service environment.

Some rapid-setting materials obtain their strength development and expansion from the formation of ettringite. If the level of expansion is high and the time to attain the maximum levels of expansion is long, strength retrogression may occur. The potential for delayed expansion resulting from insufficient initial curing followed by rewetting should be recognized.

Since some of these materials may contain abnormally high levels of alkali or aluminate to provide expansion, their exposure to sulfates and reactive aggregates should be limited.

c. *Applications.* Rapid-setting cements are especially useful in repair situations where an early return to traffic is required, such as repair of pavements, bridge decks, and airport runways.

d. *Standards.* ASTM C 928 covers packaged, dry, cementitious mortar or concrete materials for rapid repairs to hardened hydraulic-cement concrete pavements and structures. ASTM C 928 does not provide bond strength or freeze-thaw durability requirements. Also, a current footnote cautions the user to check on exposure conditions (sulfate exposure and alkali reactivity) that are not covered in the specification. Therefore, additional testing should be performed at anticipated application temperatures to verify if properties not covered in the specification are important for a given project. Substantial advances in the compounding of rapid setting ce-

ments has taken place in recent years. Such materials are now readily available for batching and mixing in large quantities using standard equipment including ready-mixed concrete trucks.

3.2.11 Shotcrete—Shotcrete is a mixture of portland cement, sand, and water "shot" into place by compressed air. In addition to these materials, shotcrete can also contain coarse aggregate, fibers, and admixtures. Properly applied shotcrete is a structurally adequate and durable repair material which is capable of excellent bond with existing concrete or other construction materials.

a. *Advantages.* In repair projects where thin sections less than 6 in. (150 mm) in depth and large or small surface areas with irregular contours or shapes are involved, shotcrete may be more economical than conventional concrete because of the savings in forming costs.

Shotcrete can be applied overhead in normal applications, and materials can be mixed and transported several hundred feet to the nozzleman in project sites with restricted access. Mechanical equipment is also available for remote placement of shotcrete.

b. *Limitations.* The successful application of shotcrete is dependent on the training, skill, and experience of the nozzleman. The nozzleman should be required to demonstrate his skill by placing a test panel that reflects the site conditions. His performance should be evaluated and approved before he is allowed on the job.

Dust and rebound require special attention in indoor applications.

c. *Applications.* Shotcrete has been used to repair deteriorated concrete bridges, buildings, lock walls, dams, tunnels, and other structures. The performance of shotcrete repair has generally been good. However, there are some instances of poor performance. Major causes of poor performance are inadequate preparation of the old surface and poor workmanship. Satisfactory shotcrete repair is contingent upon proper surface treatment of old surfaces to which the shotcrete is being applied.

d. *Standards.* ACI 506.2 provides specifications for shotcrete construction.

ASTM C 1116 covers the materials proportions, batching, delivery, and testing of fiber-reinforced concrete and shotcrete.

3.2.12 *Shrinkage-compensating concrete*—Shrinkage-compensating concrete is an expansive-cement concrete which is used to minimize cracking caused by drying shrinkage. The basic materials and methods are similar to those necessary to produce high-quality portland cement concrete. Consequently, the characteristics of shrinkage-compensating concrete are, in most respects, similar to those of portland-cement concrete.

a. *Advantages.* When properly restrained by reinforcement, shrinkage-compensating concrete will expand an amount equal to or slightly greater than the anticipated drying shrinkage. Subsequent drying shrinkage will reduce these expansive strains but, ideally, a residual expansion will remain in the concrete, thereby eliminating shrinkage cracking. The joints used to control shrinkage cracking can be eliminated along with the normal provisions for waterstops and load transfer mechanisms. However, where a watertight condition is essential, the elimination of waterstops is not recommended.

b. *Limitations.* Although its characteristics are in most respects similar to those of portland-cement concrete, the materials, selection of proportions, placement, and curing must be such that sufficient expansion is obtained to compensate for subsequent drying shrinkage. The criteria and practices necessary to ensure that expansion occurs at the time and in the amount required are given in ACI 223.

Provisions must be made to allow for initial expansion of the material to provide positive strain on the internal steel restraint. Consequently, shrinkage-compensating concrete will not be effective in bonded overlays on portland cement concrete because the substrate will provide too much external restraint.

c. *Applications.* Shrinkage-compensating concrete has been used to minimize cracking caused by drying shrinkage in replacement concrete slabs, pavements, bridge decks, and structures. Also, shrinkage-compensating concrete has been used to reduce warping tendencies where concrete is exposed to single face drying and carbonation shrinkage.

d. *Standards.* ASTM C 845 provides standards for expansive hydraulic cement and limits including strength, setting time, and expansion of the cement. Mortar and concrete expansions are usually determined in accordance with ASTM C 806 and C 878, respectively. Adequacy of concrete should be checked and used as outlined in ACI 223.

3.2.13 Silica-Fume Concrete—Silica fume, a by-product in the manufacture of silicon and ferrosilicon alloys, is an efficient pozzolanic material. Adding silica fume and a high-range water-reducing admixture to a concrete mixture will significantly increase compressive strength, decrease permeability, and thus improve durability (ACI 234R). Silica fume is added to concrete in either liquid or powder form in quantities of 5 to 15 percent by weight of cement. Compressive strengths of 12,000 to 15,000 psi (83 to 103 MPa) can be attained with silica-fume concrete.

a. *Advantages.* The initial commercial interest in silica fume was for high-strength concrete; however, it is being added to concrete today in some cases as a cement replacement material or as a property enhancing material to improve quality and performance in a wide range of applications.

Silica-fume concrete requires no significant changes from the normal transporting, placing, and consolidating practices associated with conventional concrete.

b. *Limitations.* Typically, as silica fume dosage increases, the concrete will become more cohesive, and it will be more susceptible to plastic shrinkage cracking. However, placing and finishing crews have been able to overcome these differences without any significant difficulties (Holland, 1987). Silica-fume concrete has little or no bleed water, which makes it difficult to provide a steel trowel finish, if required.

The minimum curing temperature should be 40 F (4 C). Also, wet curing for a minimum of 7 days is recommended.

c. *Applications.* The first major applications of silica-fume concrete in the United States were for repair of hydraulic

structures subjected to abrasion-erosion damage (Holland and Gutschow, 1987). The high strength of silica-fume concrete and the resulting abrasion-erosion resistance appear to offer an economical solution to abrasion-erosion problems, particularly in those areas where locally available aggregate otherwise might not make acceptable concrete.

Silica-fume concrete has been used extensively in overlays on parking structures and bridge decks to reduce the intrusion of chloride ions into the concrete.

d. *Standards.* ASTM C 1240 has recently been published to cover silica fume.

3.2.14 *Bonding materials*—Bonding materials can be used to bond new repair materials to an existing prepared concrete substrate. Bonding materials are of three types: epoxy based, latex based, and cement based.

a. *Epoxy.* Epoxy systems are covered in ASTM C 881. Care should be taken when using these materials in hot weather. High temperatures may cause premature curing and the creation of a bond breaker. Most epoxy resin bonding materials create a moisture barrier between the existing substrate and the repair material. Under certain conditions a moisture barrier could result in failure of the repair, when moisture is trapped in the concrete directly behind the moisture barrier and freezing occurs in this zone.

b. *Latex.* Latex systems are covered in ASTM C 1059. Latex bonding agents are classified as Type I—Redispersible and Type II—Non-redispersible. Type I bonding agents can be applied to the bonding surface several days prior to placing the repair materials; however, the bond strength is less than that provided by Type II bonding agents. Type I bonding agents should not be used in areas subject to water, high humidity, or structural applications. Type II systems act as bond breakers once they have skinned over or cured.

c. *Cement.* Cement based systems have been used for many years. Cement bonding systems use neat portland cement or a blend of portland cement and fine aggregate filler generally proportioned one to one by weight. Water is added to provide a uniformly creamy consistency.

3.3—Polymer materials

The improvement of properties of hardened concrete by the addition of polymers is well documented. A bibliography of major references covering polymers in concrete and a glossary of terms are included in ACI 548.1R. This guide presents information on various types of polymer materials and on their storage, handling, and use, as well as on concrete formulations, equipment to be used, construction procedures, and applications.

Three basic types of concrete materials use polymers to form composites: a) polymer-impregnated concrete (PIC), b) polymer-modified concrete (PMC), and c) polymer concrete (PC). Each type of material will be discussed in the following sections.

3.3.1 *Polymer-impregnated concrete*—PIC is a hydrated portland-cement concrete that has been impregnated with a monomer that is subsequently polymerized. Impregnation is usually done using monomers which contain a polymerization initiator that can be activated by heat. The most widely used monomer is methyl methacrylate, although other monomers have been used. With polymer loadings of 1.5 to 2.5 percent by weight, and depths of impregnation of at least $^{1}/_{4}$ in., (6 mm) and up to $1^{1}/_{2}$ in. (38 mm), significant improvements in durability can be achieved. It is important to achieve a complete shell of impregnated concrete at the exposed surfaces.

a. *Advantages.* Almost all existing types of concrete, whether they were cast with impregnation in mind or not, can be impregnated provided the proper procedures are followed (ACI 548R). The impregnation of concrete surfaces with a suitable polymer has been shown to improve several important properties, including abrasion resistance; resistance to penetration by, and damage from water, acids, salts, and other deleterious media; and resistance to cycles of freezing and thawing.

b. *Limitations.* Polymer impregnation reduces the permeability of concrete and thereby increases its durability in exposure to aggressive agents. However, impregnation does not render the concrete completely impermeable, and since concrete is still exposed, aggressive agents, such as sulfuric acid, will attack the concrete slowly.

Cracks that are not sealed could serve as channels for ingress of aggressive agents into the concrete thereby defeating the purpose of the surface impregnation treatment. Cracks are also likely to occur during drying of the concrete prior to application of the monomer, and all of these cracks may not be filled during the impregnation process. All cracks must be filled with the polymer to achieve a reduction in permeability and corresponding increase in durability.

c. *Applications.* Polymer impregnation has been applied to existing concrete structures to improve durability, reduce maintenance requirements, and restore deteriorated concrete. The process has been used in a variety of applications including bridge decks, spillways, stilling basins, curbstones, concrete pipes and mortar-lined steel pipes, and deteriorated buildings.

d. *Standards.* None.

3.3.2 *Polymer-modified concrete*—Polymer-modified concrete (PMC) has at times been called polymer-portland-cement concrete (PPCC) and latex-modified concrete (LMC). It is identified as portland cement and aggregate combined at the time of mixing with organic polymers that are dispersed or redispersed in water. This dispersion is called a latex, and 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 homo-polymer if it is made by the polymerization of one monomer or a copolymer if two or more monomers are polymerized.

In this section, the use of the term "polymer-modified concrete" includes both mortar and concrete.

Polymer dispersions are added to the concrete 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 pen-

etration by water and by dissolved salts, and improved resistance to frost action.

Of the wide variety of polymers investigated for use in PMC, 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 latexes commonly used include polymers and copolymers of vinyl acetate.

When emulsified and mixed with concrete, epoxies provide excellent freeze-thaw resistance, significantly reduced permeability, and improved chemical resistance. Bond is excellent and flexural, compressive, and tensile strengths are high. However, epoxy emulsions have had limited use in concrete.

Mixture proportions depend on the specific application and the type of polymer used in the PMC. Polymer levels of 10 to 20 percent polymer solids by weight of cement are required for most desired applications. Typical water-cement ratios for workable PMC 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).

a. *Advantages*. Latex-modified concrete (LMC) overlays have exhibited excellent long-term performance. Properly installed overlays are highly resistant to freeze-thaw damage, and they exhibit minimal bond failure after many years of service. LMC 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.

Mixing and handling of PMC is similar to conventional portland cement concrete and mortar. Curing, however, is different. Whereas conventional concrete requires extended periods of moist curing, PMC generally requires one day to two days of moist curing followed by air curing. The PMC is placed in service when it has developed sufficient strength, which is dependent upon the hydration of the cement.

An advantage of latex-modified concrete is its good workability and ease of application when compared to similar systems.

The bonding characteristics of latex-modified concrete are excellent (Kuhlmann, 1990) and latex-modified concrete usually exhibits low permeability (Kuhlmann, 1984).

Styrene-butadiene LMC has excellent durability for exterior exposures or environments where moisture is present. Surface discoloration will occur when the concrete is exposed to UV light. Where such discoloration is not acceptable, acrylic polymers should be used.

b. *Limitations*. Like conventional concrete, latex modified 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).

It is recommended that mobile, continuous mixers, fitted with an additional storage tank for the latex, be used for large applications of LMC.

Like many mixtures with a low water-cementitious materials ratio, LMC has a tendency for plastic shrinkage cracking during field placement. Special precautions are necessary when the evaporation rate exceeds 0.1 lb/ft^2/hr (0.5 kg/m^2/hr) (ACI 308, ACI 548.4).

Latex modified concrete, similar to other portland cement based materials, is susceptible to shrinkage cracking, which may allow ingress of chloride ions in some applications.

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.

c. *Applications.* PMC applications include overlays of bridge decks, parking structures and floors, and patching of any concrete surfaces. Styrene butadiene latex has been commonly used for repair of bridges, parking decks and floors. Acrylic latexes have been used for floor repair and patching and are particularly suitable in exterior white cement applications where color retention is important.

Latex modified concrete is most commonly used for overlays. It is normally applied in sections ranging from $^3/_4$ to 2 in. (19 to 50 mm) thick. These systems restore lost sections and provide a new, high-strength wearing surface that is very durable against weathering.

Although used as overlay materials, polymer-modified concretes are effective patching materials. Since most patches and repairs in which PMC is used are relatively shallow, mixture proportions similar to those shown in ACI 548.3R should be considered.

d. *Standards.* ASTM C 685 covers concrete made from materials continuously batched by volume and mixed in a continuous mixer. Tests and criteria for batching accuracy and mixing efficiency are specified. ACI 548.4 covers the placement of styrene-butadiene latex-modified concrete overlays for bridge decks.

3.3.3 *Polymer concrete*—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.

PC has been made with a variety of resins and monomers including polyester, epoxy, furan, vinylester, methyl methacrylate (MMA), and styrene (ACI 548.1R). Polyester resins are attractive because of moderate cost, availability of a great variety of formulations, and moderately 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 adhesion to wet surfaces. Detailed information on the use of epoxy compounds with concrete is available (ACI 503R).

The properties of PC are largely dependent upon 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 a) rapid curing, b) high tensile, flexural, and compressive strengths, c) good adhesion to most surfaces, d) good freeze-thaw durability, e) low perme-

ability to water and aggressive solutions, and f) good chemical resistance.

a. *Advantages*. PC can provide a fast-curing, high-strength patching material that is suitable for repair of portland cement concrete structures. PC is mixed, placed, and consolidated in a manner that is similar to conventional concrete. With some harsh mixtures, external vibration is required.

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

Epoxy mortars generally 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.

b. *Limitations*. Organic solvents may be needed to clean equipment when using polyesters and epoxies. Volatile systems such as MMA evaporate quickly and present no cleaning problems. However, such systems are potentially explosive and require nonsparking and explosion-proof equipment.

It should be recognized that 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 one hour. Also, high or low ambient and concrete temperatures may significantly affect polymer cure time or performance.

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

Shrinkage characteristics of PC's must be closely evaluated so that unnecessary shrinkage cracking is avoided.

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

Only a limited number of polymer systems is appropriate for repair of wet concrete surfaces. In general, the aggregates used in PC should be dry in order to obtain the highest strengths.

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

Conventional concrete generally will not bond to cured PC, and compatibility of the systems should be considered.

c. *Applications*. Many PC patching materials are primarily designed for the repair of highway structures where traffic conditions allow closing of a repair area for only a few hours. However, PC's are not limited to that usage and can be formulated for a wide variety of applications.

PC is used in several types of application; 1) fast-curing, high-strength patching of structures, and 2) thin ($^3/_{16}$ to $^3/_{4}$-in. (5 to 19 mm) thick) overlays for floors and bridge decks.

Polymer mortars have been used in a variety of repairs where only thin sections (patches and 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.

d. *Standards*. ACI 503.4 is a specification for repair of defects in hardened portland cement concrete with a sand-filled mortar using an adhesive binder such that as defined in ASTM C 881. It includes requirements for adhesive labeling, storage, handling, mixing and application, surface evaluation and preparation, as well as inspection and quality control.

ASTM C 881 covers two-component, epoxy resin bonding systems for application to portland cement concrete, which are able to cure under humid conditions and bond to damp surfaces.

3.4—Material selection

It is apparent from the preceding discussion that there is a wide variety of conventional and specialty materials available for repair of concrete. While this large selection provides a greater opportunity to match material properties with specific project requirements, it also increases the potential for selection of an inappropriate material. Bond and compressive strengths are obviously important material properties in many repairs, and they are frequently provided by material suppliers. However, some other material properties that can be of equal or greater importance (Warner, 1984) are discussed in the following.

3.4.1 *Coefficient of thermal expansion*—It is important to use a repair material with a coefficient of expansion similar to that of the existing concrete. Thermal compatibility is particularly important when making large patches or placing overlays. If there is a large difference in the thermal properties of the two materials, significant changes in temperature could cause failure either at the interface or within the material of lower strength. While this factor is most important in environments which are frequently subject to large temperature changes, it should also be considered in environments in which temperature changes are not as large or frequent.

3.4.2 *Shrinkage*—Since most repairs are made on older portland cement concrete that will not undergo further significant shrinkage, the repair material must also be essentially shrinkage-free or be able to shrink without losing bond. Shrinkage of cementitious repair materials can be reduced by using mixtures with very low water-cement ratios or by using construction procedures that minimize the shrinkage potential. Examples include dry pack and preplaced-aggregate concrete.

3.4.3 *Permeability*—Good quality concrete is relatively impermeable to liquids, but when moisture evaporates at a surface, replacement liquid is pulled toward the dry surface by capillary action. If impermeable materials are used for large patches, overlays, or coatings, moisture that rises up through the base concrete can be trapped between the concrete and the impermeable repair material. The entrapped moisture can cause failure at the bond line or critically satu-

rate the base concrete and cause failure in freezing and thawing if the base concrete is not adequately air entrained (U. S. Army Corps of Engineers, 1986).

3.4.4 *Modulus of elasticity*—For repaired areas that will be subjected to loading parallel to the bond line, it is necessary to ensure that the modulus of elasticity of the repair material closely matches that of the original concrete. If the moduli of the two materials differ, the loading may result in differing deformations that can result in failure of the repair material or of the original concrete.

3.4.5 *Chemical properties*—Special attention has been directed in recent years to problems involving corrosion of embedded reinforcing. A pH close to 12 (alkaline environment) for concrete will provide corrosion protection to embedded reinforcing. However, repair materials with moderate to low pH values may provide little, if any, protection to embedded reinforcing. When such materials must be used, because of constraints such as cure time or strength requirements, additional protection for the existing reinforcement should be considered. This protection could include such techniques as cathodic protection or coatings. Each system has its own cost-benefit ratio and should be evaluated for each specific project.

3.4.6 *Electrical properties*—A repair material's resistivity or electrical stability may also affect the performance of corrosion damaged concrete following repair. Materials that have high resistance tend to isolate repaired areas from adjacent undamaged areas. It is commonly accepted that differentials in electrical potential resulting from variations of permeability or chloride content between the repair material and the original concrete could increase corrosion activity, resulting in premature failure.

The conditions under which the repair material will be applied and its anticipated service conditions are also important considerations in material selection. Almost every repair project has unique conditions and special requirements, and only after these have been thoroughly examined can the final repair criteria be established. Once the criteria are known, it will often be found that more than one material can be used with equally good results. Final selection of the material or combination of materials should then take into consideration the ease of application, cost, and available labor skills and equipment (Warner, 1984). In areas where failure of a repair could create a safety hazard, such as repairs on a wall above a public area, the repair should be designed with adequate mechanical anchorage.

3.4.7 *Color properties*—For repair of architectural concrete surfaces, color of the repair material should not differ appreciably from the adjacent surface. Trials should be made on a job site mockup prior to beginning actual production work.

Protective systems are materials and methods that reduce corrosion of metals in concrete and deterioration of concrete by limiting the intrusion of moisture, chloride, and other contaminants into the concrete by coatings or by electrical-chemical principles. Protective systems also include materials and methods that increase surface abrasion or impact resistance, or improve the resistance to other deleterious influences.

CHAPTER 4—PROTECTIVE SYSTEMS
4.1— Surface Treatments

Surface treatments for concrete repair for the purpose of this guide are grouped into the following general classifications: penetrating sealers, surface sealers, high-build coatings, membranes, and overlays.

4.1.1 *Uses*—Surface treatments include horizontal or vertical applications. The techniques and materials selected must be consistent with the intended use. The objective is to limit corrosion by establishing conditions that reduce the free water in the concrete while preventing further moisture or chloride intrusion. Although results have varied, surface treatments have been effective in substantially slowing reinforcement corrosion in laboratory tests, and some have performed well in field applications. Quality materials and workmanship are essential.

4.1.2 *Precautions*—Assure compatibility between the intended treatment, the repair materials, and the existing concrete substrate. Avoid encapsulating concrete between non-breathing surface treatments. Follow manufacturer's recommendations and limitations.

4.1.3 *Properties*—The properties of surface treatments affecting their selection are discussed below and summarized in Table 4-1. The surface treatments are generically classified to facilitate this presentation, but the summary lists characteristics based on limited data from laboratory tests and field performance of specific formulations of proprietary products. A particular product should only be selected based on its performance track record and results of standardized or comparative tests. Studies which directly measure performance with respect to water absorption, durability in northern and southern climates, and resistance to reinforcement corrosion are discussed later in this section. References to ASTM standards for sealers and coatings are given in Table 4-2.

The surface treatment classifications discussed are those commonly used for concrete repair and protection against reinforcement corrosion in particular. Not all possible classifications are addressed. Many other types of systems may be appropriately used in conjunction with concrete repair.

The costs of the various surface treatments vary greatly. Accurate costs can only be obtained from the manufacturer and installer for a particular project.

4.1.4 *Installation requirements*—Most surface treatments must be applied to a clean, dry, and sound substrate at moderate temperature and humidity conditions in a well-ventilated space. A relatively smooth surface is needed for liquid-applied membranes. Because these conditions do not always prevail, the difficulty and cost in achieving the appropriate installation conditions may influence the choice of a system.

Prior to applying most surface treatments, all concrete repairs must be completed and should be allowed to cure for a minimum of 28 days.

Surface preparation is an important consideration and the method depends on the type of protective system. Techniques include scarification, brushing or grinding, abrasive blasting, shotblasting, flame cleaning, and acid etching. Cady, Weyers, and Wilson (1984) and Gaul (1984) discuss surface preparation requirements and methods. All dust and

debris resulting from surface preparation should be removed prior to applying the surface treatment.

It is also important to consider compatibility and installation details of terminations at expansion and control joints, door and window openings, drains, and curbs. It is imperative to ventilate any flammable and noxious fumes that may be produced. Manufacturer's specifications should include installation requirements. Moisture in the slab at time of application, temperature, presence of contaminants, as well as other factors will affect the success in applying a system.

4.1.5 *Performance characteristics*

a. *Water permeability*. Resistance to water absorption is a critical factor in protective systems. Water permeability is a measurement of the quantity of water that can pass through a surface treatment over a period of time.

b. *Vapor permeability.* While surface treatments must resist water, they must allow concrete to dry out, particularly if placed over new concrete repairs or on the inside face of foundation walls or on slabs-on-grade. Moisture vapor transmission is the quantity of water vapor that can pass through a protective system over a period of time.

c. *Resistance to reinforcement corrosion*. The water and vapor permeability characteristics described above are indirect measures of the resistance of concrete to reinforcement corrosion. Penetration of chemical or salt solution through concrete is likely to cause localized corrosion of reinforcing steel. A primary reason to provide surface treatments is to increase the resistance to reinforcement corrosion by providing a less corrosive environment. Studies of different protective systems to resist corrosion have been documented by Pfeifer and Scali (1981) and by Pfeifer, Landgren, and Zoob (1987).

d. *Crack bridging.* Moisture penetration through cracks may defeat the purpose of the surface treatment by allowing localized reinforcement corrosion. Penetrants and surface sealers do not have significant crack bridging capabilities, although the hydrophobic nature of the silanes may prevent moisture intrusion into narrow cracks. Elastomeric membrane systems generally have sufficient thickness and flexibility to bridge narrow cracks even if the crack width fluctuates. Cracks wider than about 10-15 mils (0.25-0.375 mm) should be routed and sealed prior to application of the membrane. Penetrants and surface sealers can be successfully used in conjunction with routing and sealing or other crack repair. Other sections of this guide discuss crack repair techniques. The data from the studies cited above should be reviewed with caution because these studies were conducted primarily on uncracked samples which were coated prior to exposure simulating northern and southern climates.

e. *Skid resistance*. Penetrants do not affect the skid resistance (a measure of the frictional characteristics) of the concrete surface. Because penetrants are located at or beneath the surface, they are subject to wear to the same extent as the concrete surface. Surface sealers and high build coatings may make the surface less skid resistant, whereas membrane systems and overlays have the potential to make the surface more skid resistant. See Table 4.1.

f. *Appearance*. Except for penetrants, most surface treatments alter the appearance of the concrete. This can be advantageous because the contrast between original concrete and repairs can be hidden. Most surface sealers are transparent, which results in a wet or glossy appearance, although some can be pigmented. High build coatings are available in a variety of colors. Membranes and membrane top coats are usually gray or black, but some manufacturers offer several other colors (which may have a tendency to fade). The gritty surface of a membrane top coat is difficult to keep clean.

4.1.6. *Penetrating sealers*

a. *Description*. Penetrating sealers are materials which after application are generally within the substrate of the concrete. Depth of penetration will vary by the product and with the properties of the concrete on which the sealer is applied.

Table 4.1— Summary of surface treatments

Types	Generic classification(s)	Instillation requirements	Durability characteristics	Performance characteristics
Sealers	Boiled linseed oil Sprayed Approximately 50 deg F (10C) or above	Clean, dry and sound surface Poor resistance to UV radiation	Improves freeze-thaw durability Frequent applications required	Darkens concrete slightly Does not bridge cracks
	Alkyl-alkoxy- silane Siloxanes	Surface free of pretreatments Sprayed, brushed or rolled Ventilation required	Improves freeze-thaw durability Reduces salt penetration Reduces rate of corrosion	Improved resistance to water absorption and reinforcement corrosion Does not bridge cracks
	High-molecular weight methacrylate	Clean, dry, and sound surface Sprayed, brushed, rolled, or squeegeed	Variable UV radiation resistance Prevents moisture from penetrating cracks	Seals cracks
Coatings	Epoxy Urethane or neoprene membrane/epoxy top coat system Rubberized asphaltic top coat system Urethane Membrane/urethane topcoat system	Clean. dry, and sound surface Sprayed, brushed, rolled or squeegeed Approximately 50 deg F (10 C) or above Ventilation required Level surface typically required	Generally improves freeze-thaw durability Fair to good abrasion resistance Variable UV radiation resistance	Generally good resistance to water absorption Unknown resistance to reinforcement corrosion Bridges small cracks
Overlays	Concrete Polymer concrete Polymer-modified concrete	Clean, sound, and roughened surface Hand or machine applied Generally above freezing Ventilation may be required	Improves freeze-thaw durability Excellent abrasion resistance	May add weight Architectural finish is possible Protects structural concrete and reinforcing May improve structural capacity

Table 4.2—Testing of sealers and coatings for reinforced concrete

A. Protective Properties

1. Artificial or Accelerated Weathering

ASTM D 1653 Test Method for Water Vapor Transmission of Organic Coating Films

ASTM E 96 Test Methods for Water Vapor Transmission of Materials

2. Water Absorption

ASTM C 67 Test Methods of Sampling and Testing Brick and Structural Clay Tile

ASTM C 642 Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete

3. Chloride Ingress

AASHTO T 259, Resistance of Concrete to Chloride Ion Penetration

B. Durability

1. Natural Weathering

ASTM D 4141 Practice for Conducting Accelerated Outdoor Exposure Tests for Coatings

2. Artificial or Accelerated Weathering

ASTM G 26 Practice for Operating Light Exposure Apparatus (Xenon-Arc Type) With and Without Water for Exposure of Nonmetallic Materials

3. Salt Spray Resistance

ASTM B 117 Test Method of Salt Spray (Fog) Testing

4. Freeze Thaw/ Scaling

ASTM D 2247 Practice for Testing Water Resistance of Coatings in 100% Relative Humidity

6. Resistance to Alkali

ASTM D 1647 Test Method for Resistance of Dried Films of Varnishes to Water and Alkali

7. Light Stability

ASTM D 2620 Test Method for Light Stability of Clear Coatings

8. Chalking

ASTM D 4214 Test Methods for Evaluating Degree of Chalking of Exterior Paint Films

9. Water Swelling

ASTM D 2247 Practice for Testing Water Resistance of Coatings in 100% Relative Humidity

10. Resistance to Wind-Driven Rain

ASTM E 514 Test Method of Water Permeance of Masonry

Fed. Spec. TT-C-555B Coating, Textured (for Interior and Exterior Masonry Surfaces)

Fed. Spec. TT-P-1411A Paint, Copolymer-Resins Cementitious (for Waterproofing Concrete and Masonry Walls)

ASTM D 412 Test Methods for Vulcanized Rubber and Thermoplastic Rubbers and Thermoplastic Elastomers—Tension

ASTM D522 Test Methods for Mandrel Bend Test of Attached Organic Coatings

ASTM D 1642 Test Methods for Elasticity or Toughness of Varnishes

ASTM D 2370 Test Method for Tensile Properties of Organic Coating

ASTM D 522 Test Methods for Mandrel Bend Test of Attached Organic Coatings

ASTM D 1642 Test Methods for Elasticity or Toughness of Varnishes

ASTM D 429 Test Method for Rubber Property—Adhesion to Rigid Substrates

ASTM D2197 Test Methods for Adhesion of Organic Coatings by Scrape Adhesion Tester

ASTM D 3359 Test Methods for Measuring Adhesion by Tape Test

ASTM D 4541 Method for Pull-Off Strength of Coatings Using Portable Adhesion-Testers

ASTM D2794 Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact)

6. Coefficient of Friction

ASTM D 2047 Test Method for Static Coefficient of Friction of Polish-Coated Floor Surfaces as Measured by the James Machine

B. Durability (continued)

7. Chemical Resistance

ASTM C 267 Test Method for Chemical Resistance of Mortars

8. Crack Bridging

ASTM C 836 Specification for High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane for Use with Separate Wearing Course

C. Performance Properties

1. Elongation/Elasticity

D. Physical Properties

1. Viscosity

ASTM D 2196 Test Method for Rheological Propertie2 of Non-Newtonian Materials by Rotational (Brookfield) Viscometer

2. Hardness

ASTM D 1474 Test Methods for Indentation Hardness of Organic Coatings

ASTM D 2134 Test Method for Determining the Hardness of Organic Coatings with a Sward-Type Hardness Rocker

ASTM D 2240 Test Method for Rubber Property—Durometer Hardness

ASTM D 3363 Test Method for Film Hardness by Pencil Test

3. Specific Gravity

4. Drying Time

ASTM D 1640 Test Methods for Drying, Curing, or Film Formation of Organic Coatings at Room Temperature

5. Nonvolatile Content

ASTM D 1353 Test Method for Nonvolatile Matter in Volatile Solvents for Use in Paint, Varnish, Lacquer, and Related Products

6. Flash Point

ASTM D 56 Test Method for Flash Point by Tag Closed Tester

ASTM D 93 Test Methods for Flash Point by Pensky-Martens Closed Tester

ASTM D 3278 Test Method for Flash Point of Liquids by Setaflash-Closed-Cup Apparatus

7. Flame Spread, Smoke Density

ASTM E 84 Test Method for Surface Burning Characteristics of Building Materials

8. Gloss

ASTM D 523 Test Method for Specular Gloss

9. Coating Thickness

ASTM D 4138 Test Method for Measurement of Dry Film Thickness of Protective Curing Systems by Destructive means

10. Cure Time

11. Effect on Potable Water

NSF Standard 61 Drinking Water Components—Health Effects

12. Microbiological Attack

ASTM D 3274 Test Method of Evaluating Degree of Surface Disfigurement of Paint Films by Microbial (Fungal or Algal) Growth or Soil and Dirt Accumulation

ASTM D 3456 Practice for Determining by Exterior Exposure Tests Susceptibility of Paint Films to Microbial Attack

Depth of penetration is determined to a large degree by the size of the sealer molecule and the size of the pore structure in the concrete. While deep penetration may be desirable, especially for surfaces subjected to abrasion, it is not the most important criterion for sealer effectiveness. Such products include, but are not limited to, boiled linseed oil, silanes, siloxanes, certain epoxies, and high molecular weight methacrylates.

 b. *Applications and limitations.* Penetrating sealers may be roller-, squeegee- or spray-applied to the concrete substrate.

Proper surface preparation is important for successful application due to the sensitivity of penetrating sealers to contaminants and previously applied sealers in the substrate. Ultraviolet (UV) and abrasion resistance are generally good. Penetrating sealers will not bridge new or existing cracks.

4.1.7 *Surface sealers*

a. *Description*. Surface sealers are products of 10 mils (0.25 mm) or less in thickness that generally lay on the surface of the concrete. Such products include varieties of epoxies, polyurethanes, methyl methacrylates, moisture-cured urethanes and acrylic resins. Certain paints whether oil based or latex based (such as styrene-butadiene, polyvinyl acetate, acrylic or blends of these with other polymers dispersed in water), would be included in this classification if less than 10 mils (0.25 mm) thick. The dry film thickness of surface sealers and paints ranges from 1 to 10 mils (0.03 to 0.25 mm). Although these products may be pigmented, they will not appreciably alter the texture of the surface and most surface blemishes will reflect through.

b. *Application and limitations.* The materials may be applied with brush, roller, squeegee or spray. The chemical carriers within some of the products may cause application limitations. The manufacturer's safety recommendations must be followed. Surface sealers will, in general, reduce skid resistance. They will not bridge moving cracks, but may be effective in closing (not bridging) small, non-moving cracks. Many of these products are affected by UV and will wear under surface abrasion. Epoxies and methyl methacrylates, however, do show good resistance to abrasion and perform better than other products in this classification. Surface preparation is important for all these products.

4.1.8 *High-build coatings*

a. *Description*. High-build coatings are materials with a dry thickness greater than 10 mils (0.25 mm) and less than 30 mils (0.75 mm) applied to the surface of the concrete. The base polymers of such products include, but are not limited to, acrylics, styrene-butadienes, polyvinyl acetates, chlorinated rubbers, urethanes, polyesters, and epoxies. High-build coatings will alter the appearance of the surface, may be pigmented, and will partially mask blemishes in the concrete surface.

b. *Applications and limitations.* These products may be applied with brush, roller, squeegee, or spray. In normal environments the coating must be resistant to oxidation as well as UV and infrared radiation exposure. On floors, resistance to abrasion and punctures as well as resistance to mild chemicals (salts, grease and oil, battery acid, and detergents) are also important.

In addition to preservation of the coating material, the bond between the coating and concrete substrate must remain intact. Even with proper surface preparation, the bond can break down. If the coating is highly impermeable to water vapor, water may condense at the concrete/coating interface and destroy the bond.

Epoxy resins are commonly used repair materials that generally have very good bonding and durability characteristics. The resins can be mixed with fine aggregates to improve abrasive and skid resistance. Some high-build coatings, including epoxies without aggregate, when used in horizontal applications, may result in a very slippery surface when wet and may not be suitable for pedestrian or vehicular traffic. The non-elastomeric high-build coatings generally do not bridge moving cracks, but may be effective in filling small, non-moving cracks. These products have better wear characteristics than thinner systems.

A guide to the use of coatings as a protective barrier is reported by ACI 515.1R. A coating intended to reduce reinforcement corrosion in repair work may also be required to waterproof the structure, protect against chemical attack, or improve the appearance.

4.1.9 *Membranes*

a. *Description*. Membrane systems are surface treatments with a thickness of greater than 30 mils (0.7 mm) and less than 250 mils (6 mm) applied to the surface of the concrete. Such products include, but are not limited to, urethanes, acrylics, epoxies, neoprenes, cement, polymer concrete, certain methyl methacrylates, and asphaltic products. These products significantly alter the appearance and mask blemishes in the concrete surface. Elastomeric membranes fall into this group as well as some high-build coatings.

b. *Application and limitations.* These products may be applied by brush, squeegee, roller, trowel, or spray. Most of these membranes are resistant to water absorption and bridge small (less than 0.01 in. [0.25 mm]) moving or non-moving cracks. Membranes with rigid urethane mortar or epoxy mortar top coat offer reasonable skid and abrasion resistance under traffic. Frequent maintenance of membranes in parking structures may be required at steep ramps and turning, starting, and stopping areas.

Tests which measure performance characteristics of elastomeric membranes, particularly traffic deck membrane systems, are quite limited. Manufacturers usually list a variety of different (non-standardized) test results in their technical data sheets which are conducted in their own laboratory under room temperature conditions.

Standardized test results from independent laboratories for traffic bearing membrane systems should be compared for key performance characteristics such as: permeability, elongation, tensile strength, tear strength, adhesion, modulus of elasticity, abrasion resistance, low temperature flexibility, and water vapor transmission.

4.1.10 *Overlays—General*

a. *Description*. Overlays are products of 250 mils (6 mm) or greater in thickness that, in general, are bonded to the surface of the concrete. Such products include, but are not limited to, polymer concrete, concrete, epoxies, certain methyl methacrylates and polymer-modified concrete. Overlays change the appearance texture and elevation of the original concrete surface. See ACI 548.1R.

b. *Application and limitations.* Overlays may be placed, troweled, screeded, sprayed, or seeded in one or more layers onto the concrete surface. The overlay will add weight proportional to its thickness. Therefore, the additional dead load must be considered in the analysis of an existing structure. Overlays can be installed to act compositely with the existing structure. Additional reinforcement may be added such as welded wire fabric, reinforcing steel, or fibers. The thick-

ness of an overlay can be used to improve the drainage characteristics of the top surface of a concrete slab. Overlays may bridge non-moving cracks; however, moving cracks may mirror through the overlay unless properly detailed. An overlay offers a choice of different colors and textures.

For an overlay to perform properly, the surface to which it is bonded must be clean and sound. Remove all laitance, dust, and debris that result from the surface preparation operations.

Cracking has been a problem in some bonded overlays. This cracking is believed to have had one of four causes: tearing the surface due to late finishing operations; plastic shrinkage from excessive drying; differential movement between the deck and the overlay due to temperature differences or drying shrinkage; or existing cracks reflected through the overlay. These can be controlled by the following procedures.

1. During the finishing operation on a cementitious overlay, the surface of the overlay must be plastic enough to receive the finish applied. If drying of the surface has occurred, there is a tendency to tear the surface and cause shallow cracks. This can be alleviated by proper timing of the finishing, and, in some cases, application of a fine mist of water to prevent evaporation losses.

2. Thin, cementitious overlays are susceptible to plastic shrinkage cracking because their high surface-to-volume ratio promotes rapid evaporation under drying conditions such as low relative humidity and wind. Also, because these concretes usually have low water-cement ratios, there is little bleed water to replace evaporated water. Determine environmental conditions to be expected when placing overlays, and consider early morning or nighttime placements to avoid drying conditions. Good curing practice, such as covering with wet burlap, will help. Control joints added within 24 hours of placement or tooled in the plastic material should reduce shrinkage stress.

3. Differential thermal movement can be minimized by cooling the deck with water prior to placement of the overlay, or placing during the early morning hours, or a combination of both.

4. Existing cracks will reflect through thin overlays. To minimize the impact of this problem, the existing cracks must be repaired and a bond breaker must be applied over the cracks.

4.1.11 *Common overlay systems*

    4.1.11.1 *Bonded portland cement concrete overlay*—Bonded portland cement concrete overlays are simply layers of concrete (usually horizontal) placed on a properly prepared existing concrete surface to restore a spalled or disintegrated surface. They provide a protective barrier to deicing salts and sometimes increase the load carrying capacity of the underlying concrete. The thickness of an overlay may range from $1^1/_2$ in. (38 mm) to almost any reasonable thickness, depending upon the purpose it is intended to serve. A portland cement based overlay may be suitable for a wide variety of applications such as resurfacing spalled or cracked concrete surfaces on bridge decks or in parking structures, increasing cover over reinforcing steel, or leveling floors. Other applications of overlays include repair of concrete surfaces which are damaged by abrasion, freezing, or fire and the repair of deteriorated pavements.

Portland cement based overlays should not be used in any application in which the original damage was caused by aggressive chemical attack that would continue to attack the portland cement in the overlay. Bonded overlays should generally not be used in situations in which there is active cracking or structural movement because the existing cracks can be reflected through the overlay. Unbonded overlays should be used in these situations.

The overlay concrete should be proportioned to match the characteristics of the substrate concrete as closely as possible. To minimize shrinkage, the water-cement ratio should be kept at the minimum that will allow proper placement and consolidation. Bonding compounds are often used with portland cement overlays. Neat sand-cement slurry placed immediately prior to the overlay has achieved successful results.

    4.1.11.2 *Latex-modified concrete (LMC) overlays*—A LMC is similar to conventional concrete except that it contains a latex and less water. Latex at the rate of 15 percent latex solids to portland cement by weight has been most commonly used in bridge and parking deck overlays. See Section 3.3.2, ACI 548.3R and ACI 548.4 for additional data concerning LMC.

The following should be considered when using LMC overlays.

1. LMC is usually produced in mobile, continuous mixers fitted with an additional storage tank, pump, and piping for the latex. It is recommended that the latex be maintained at a temperature between 45 and 85 °F (7 to 30 °C).

2. It is a characteristic of the latex to entrain a certain amount of air in the concrete and the addition of an anti-foam agent to ensure satisfactory air contents may be required. The cement should comply with ASTM C 150 for Type I, II, or III. Air-entraining cement or air-entraining admixtures should not be used.

3. LMC will tend to form a crust on the surface if allowed to dry; therefore, finishing operations should be timely to prevent tearing of the surface. In the summer, it is common for LMC placements to be in the early morning or late at night to avoid weather conditions which will aggravate this drying.

4. Roughening the parent concrete will enhance the bond. Many state departments of transportation do require a roughened surface prior to installing an LMC overlay. Prewetting the concrete substrate is recommended. The bond coat for LMC is usually produced directly by brooming the mortar fraction out of the concrete as it is discharged on the deck. Alternatively, bond coats may be produced using a separate mortar mixture that is applied in front of the concrete. The intent of a bond coat is to make intimate contact between the clean deck and the freshly-placed LMC mixture.

5. Finishing on bridge decks is usually done with a rotating drum machine, although on smaller placements vibrating screeds have been used. Metal tools for hand finishing are preferred.

6. The normal curing procedure is to apply wet burlap and polyethylene film as soon as the finishing operation is completed to prevent moisture loss from the surface. The cover should be on for a minimum of 24 to 48 hours and then removed for air drying until the LMC has achieved specified strength.

7. As LMC cures, the latex will coalesce to form a film within the concrete. This process retains some water that allows the cement to hydrate and reduce shrinkage cracking. In the dry curing stage, film formation continues, controlling the loss of excess moisture while the strength of the concrete increases. This film formation, like cement hydration, is temperature sensitive, requiring longer time at low temperatures to complete coalescence. Cylinders should be cured on the deck, in the same environment as the overlay, to properly monitor strength gain.

4.1.11.3 Epoxy overlays. Epoxy resins are commonly used repair materials that generally have very good bonding and durability characteristics (ACI 503R). These resins can be mixed with aggregates to form epoxy mortars or concretes that are suitable for some coating and overlay applications.

Overlays composed of epoxy mortars or concretes are well suited for use in areas where the concrete is being attacked by an aggressive substance such as acidic water or other chemical in the water. These overlays may also be used with caution in some instances to repair surface cracking, provided that the cause of the cracking is well understood and no movement of the concrete is expected in the future. Because the physical properties of epoxy are very different than concrete, possible applications for epoxy-based overlays and coatings must be reviewed very carefully to ensure that the proposed use is compatible with the base material. Slabs on grade or concrete walls with backfill in freezing climates should never receive an overlay or coating that is a vapor barrier. An impervious barrier will cause moisture passing from the subgrade or backfill to accumulate under or behind the barrier, leading to critical saturation of the concrete and rapid deterioration by cycles of freezing and thawing.

Evaluate the substrate to determine if the coefficient of expansion of the epoxy concrete is compatible with the substrate concrete. Failures at the bond line have commonly occurred because of the difference in thermal volumetric changes.

Repair of deteriorated concrete with epoxy overlays will involve the use of epoxy concrete or epoxy mortar. Epoxy resin systems must conform to ASTM C 881, Type III.

Aggregates are added to the system for economy and improved performance (reduced shrinkage, higher modulus of elasticity, lower coefficient of thermal expansion, and higher wear resistance) in patching applications and floor toppings. Aggregates should be clean and dry at the time of use and at a temperature similar to that expected for the epoxy resin mortar or concrete. The grading should be uniform with the smallest size retained on No. 100 sieve (150 μm) and the maximum size not to exceed one-third of the mean depth of the patch or opening to be filled. However, the recommended maximum aggregate size for epoxy-resin concrete is 1 in. (25 mm), and for epoxy-resin mortar, material passing a No. 8 (2.36 mm) sieve.

Limit the amount of aggregates to ensure complete wetting of the aggregate surfaces with resin. Vary the aggregate-resin proportions with the type and grading of the aggregate. Up to seven parts by weight of the fine aggregate can be mixed with one part of epoxy resin, but a three-to-one proportion is usually used for most fine aggregates when making epoxy mortar. For epoxy concrete the proportion of aggregate to the mixed resin may be as high as 12 to 1 by weight for aggregates in the specific gravity range of 2.50 to 2.80. The epoxy-to-aggregate ratio and temperature affect the viscosity of the system.

Machine mixing of the epoxy resin components is mandatory except for mixing volumes of 1 pint (0.5 L) or less. Epoxy mortar or concrete may be machine or hand mixed after the epoxy components have been mixed. Small drum mechanical mixers have been used successfully but are difficult to clean properly. Large commercial dough or masonry mortar mixers have been widely and successfully used and present less difficulty in cleaning. Hand mixing may be performed in metal pans with appropriate tools. When epoxy mortar is hand mixed, the mixed epoxy system is transferred to the pan and the fine aggregate is gradually added during mixing. Regardless of how the epoxy concrete is mixed, the fine aggregate is added first and then the coarse aggregate. This procedure permits proper wetting of the fine aggregate particles by the mixed epoxy system and produces a slightly "wet" mixture to which the coarse aggregate is added.

Prior to placement, a single prime coat of epoxy should be worked into the cleaned substrate by brushing, troweling, or any other method that will thoroughly wet the substrate. The epoxy mortar or concrete must be applied while the prime coat is in a tacky condition. Use hand tampers to consolidate the epoxy concrete, taking great care to trowel the mortar onto the sides and into the corners of the patch. Because of the relatively short pot life of epoxy systems, the placing, consolidating, and finishing operations must be performed quickly before the epoxy sets. Heat build-up, which occurs at the conclusion of pot life, depends on reactivity of the epoxy resin, mass of the placement, and the ambient temperature.

Do not spread excess material onto concrete adjacent to the patch because the carryover material is difficult to clean up. In finishing operations, proper surface smoothness must be achieved. The epoxy mixture tends to build up on the finishing tools requiring frequent cleaning with an appropriate solvent. After each cleaning, wipe the tool surfaces free of excess solvent.

The material used in the epoxy systems and the solvents used for cleanup may present a health hazard to some individuals. The materials may be handled safely if the manufacturer's precautionary measures are observed.

4.2—Joint sealants

The function of joint sealants in concrete is to minimize the intrusion of liquids, solids or gases, and to protect the concrete against damage. In certain applications secondary functions are to improve thermal and acoustical insulation, damp down vibration, or prevent unwanted matter collecting in crevices (ACI 504R).

Protection systems of joints include the sealing of cracks, contraction (control) joints, expansion joints, and construction joints. Joint types are discussed in the following section.

4.2.1 *Types of joints*

a. *Cracks.* The reasons that cracks occur in concrete include shrinkage, thermal changes, structural related stresses

or long term strain shortening. Prior to selecting a sealant, the reason for the cracking must be determined. Moving cracks must be identified. In some instances structural bonding of a crack may be required, whereas in other situations, restraint across the crack should be avoided.

b. *Contraction (control) joints.* These are purposely installed joints designed to regulate cracking that might otherwise occur due to the contraction of concrete (ACI 504R). These joints are often called control joints because they are intended to control crack locations. The necessary plane of weakness may be formed by reducing the concrete cross-section by tooling or saw cutting a joint (customarily within 24 hours.)

c. *Expansion (isolation) joints.* These are designed to prevent the crushing and distortion (including displacement, buckling, and warping) of the abutting concrete structural units that might otherwise occur due to the transmission of compressive forces that may be developed by expansion, applied loads, or differential movements arising from the configuration of the structure or its settlement (ACI 504R). Expansion joints are made by providing a space over the entire cross section between abutting structural units.

d. *Construction joints.* These are joints made before and after interruptions in the placement of concrete or through the positioning of precast units. Locations are usually predetermined so as to limit the work that can be done at one time to a convenient size, with least impairment of the finished structure, though they may also be necessitated by unforeseen interruptions in concreting operations. Depending on the structural design, they may be required to function later as expansion or contraction joints having the features already described, or they may be required to be soundly bonded together so as to maintain complete structural integrity. Construction joints may run horizontally or vertically depending on the placing sequence prescribed by the design of the structure (ACI 504R).

4.2.2 *Sealing methods*—Methods to seal joints include injection techniques, routing and caulking, bonding, installing premolded seals, or by installing appropriate surface protection systems (such as elastomeric membranes) discussed in Section 4.1.

ACI 504R discusses different techniques and materials to seal joints and ACI 503.1 discusses epoxy materials.

4.3—Cathodic protection

4.3.1 *Description*—Reinforcing steel in concrete is generally protected from corrosion by a passive oxide film created by the alkaline portland cement. However, when aggressive ions such as chlorides contaminate the concrete around the reinforcing steel, the passive oxide film is weakened or destroyed and corrosion of the reinforcing steel can occur.

The corrosion process is an electrochemical process where anodic and cathodic areas are formed on the steel. When the anodic and cathodic areas are electrically continuous and in the same electrolyte, corrosion at the anodic areas will occur. The corrosion is created as an electrical current flow occurs through the corrosion cell, anodes, cathode, and electrolyte. Unless mitigated, the corrosion will continue until failure oc-

curs at the anodic area. Additional information on corrosion of steel in concrete may be found in ACI 222R.

A proven procedure to control the corrosion of steel in contaminated concrete is cathodic protection. The basic principle involved in cathodic protection is to make the embedded reinforcing steel cathodic, thereby preventing further corrosion of the steel. This can be accomplished by electrically connecting the reinforcing steel to another metal that becomes the anode with or without the application of an external power supply.

Cathodic protection systems in which an external power supply is not used are referred to as sacrificial systems. The metal that is used to protect the steel is "less noble" or more prone to corrosion than the steel, for example, zinc. As such, this metal corrodes in place of the steel and the structure is protected. However, in most cathodic systems an external power supply is used to force a small amount of electric current through the reinforcing steel to counteract the flow of current caused by the corrosion process. A metal that corrodes at a very slow rate, such as platinum, is typically provided to serve an anode. This method of controlling corrosion is known as impressed current cathodic protection.

4.3.2 *Applications*—Cathodic protection can be used to protect almost any type of reinforced concrete structure. The limitations are described in Section 4.3.3. The types of structural members include:

a. *Horizontal slabs:* Parking garage decks, bridge decks, floors, roofs and balconies.

b. *Vertical members*: Wall sections, towers, and similar structures.

c. *Structural members:* Beams, columns, foundations, and bridge substructures.

4.3.3 *Limitations*—Cathodic protection systems can be used to mitigate corrosion on many types of structures. However, the following should be observed:

a. Cathodic protection will not replace corroded steel.

b. At the present time, cathodic protection is not recommended for general usage on prestressed concrete structures. A possibility of hydrogen embrittlement of the high strength steels may occur.

c. Post tensioned structures may be cathodically protected after an analysis by a corrosion engineer to determine the material of the sheathing and reinforcement, and the electrical continuity of the reinforcement.

d. The reinforcing steel must be electrically continuous for the cathodic protection to function. In structures where the reinforcing is covered with an inorganic coating such as epoxy, a determination of the electrical continuity of the reinforcing must be made before considering the use of cathodic protection.

4.3.4 *Types of cathodic protection systems*—Most cathodic protection systems contain an anode system, D.C. power source, and connecting cables. In addition to the basic components, there may be reference electrodes or other monitoring and measuring devices. The primary difference between the types of systems is the anode system and its application.

a. *Surface monitored anode systems without overlays.* These anode systems are mounted on the surface of the con-

crete and do not require a cementitious overlay. Generally, these anode systems are not used in high wear applications.

b. *Conducive mastic systems*. These consist of a conducive coating with embedded anodes on the surface of the concrete. They are used on vertical surfaces, ceilings, and columns.

c. *Plate type systems*. These consist of manufactured anode plates that are glued to the concrete surface.

d. *Surface mounted anode systems with overlays.* These anode systems are generally used on horizontal surfaces and require a cementitious overlay of 0.5 in. (13 mm) minimum thickness.

e. *Mesh type noble metal anodes.* A mesh of a noble metal anode is fixed to concrete with a multiplicity of pins and then covered with a cementitious material.

f. *Conductive polymer concrete strips.* A series of conductive polymer concrete strips containing a noble metal anode is fixed to the concrete surface and covered with a cementitious overlay.

g. *Embedded anode systems.* The anode system is embedded in the surface of the concrete or at the level of the reinforcing in new construction.

h. *Saw slot anode systems.* A series of small depth and width saw slots is made in the concrete surface. The slots are filled with a noble metal anode and a conductive polymer concrete.

i. *New construction.* Anodes can be placed at the level of the reinforcing during new construction. However, care must be taken to prevent contact between the anode and the reinforcing steel.

CHAPTER 5—STRENGTHENING TECHNIQUES

5.1—General

Prior to the repair of structural members, a structural analysis must be performed to determine if the members are overloaded or under-designed for the service loads. The analysis should consider both serviceability and strength and should include consideration of the causes of the structural failure or degradation. Based on previous evaluations and analytical results, the engineer must decide whether repair only or repair plus strengthening is required.

The following sections outline several acceptable alternatives for strengthening structural members without completely replacing them. The sections concentrate on construction methods used for strengthening such as placement of reinforcement within existing concrete or placement of new reinforcement exterior to the existing member. In all cases, the goal is to provide new reinforcement to resist tension caused by flexure, shear, torsion, and axial forces so that the strengthened structure meets the minimum requirements for strength and serviceability required by ACI 318 and other applicable building codes.

5.2—Interior reinforcing

5.2.1 *Description*—A common method of providing additional reinforcement across cracked surfaces is to install new dowels into holes drilled perpendicular to the crack surfaces. The entire length of the dowel is fixed to the concrete by the use of a bonding matrix. This repair method is shown schematically in Figs. 5.1, 5.2, 5.3, and 5.4.

The structure must be shored and jacked if it is desired to relieve the member's dead load stresses so the new reinforcing will resist the original dead load. However, at yield stress the added reinforcing would normally be effective in resisting all loads.

Several bonding materials may be used. Portland cement grouts, epoxy, and other chemical adhesives have been successfully installed within the annular space between the dowel and sides of the pre-drilled hole. Creep and other long-term behavior of such adhesives should be considered when sizing the holes and selecting the materials.

The dowels may be deformed steel reinforcing bars, stainless steel rods, or bolts. Coating steel dowels with either zinc galvanizing or fused epoxy is acceptable if all components are chemically compatible with the bonding material. The protective coating of dowels should be considered when evaluating the bond strength between concrete and dowel.

Dowels for providing shear transfer between adjoining sections of pavement may be placed in slots cut from the top to mid-depth of the adjoining sections. In one section the dowel is bonded; in the other, the dowel is unbonded using a sleeve or debonding agent.

5.2.2 *Advantages and typical uses*—Internal reinforcement can strengthen concrete cracked by flexural and shear stresses and by restrained volume changes. The procedure is simple and uses commonly available equipment.

Examples of installations of interior reinforcements are shown in Figs. 5.1, 5.2, 5.3, and 5.4. Epoxy injection is commonly used to fill all cracks after installation of the bolts and their adhesive, but before tensioning bolts. Internal post-tensioning, as shown in Fig. 5.2, is not always required.

5.2.3 *Limitations*—Avoid cutting or puncturing internal reinforcing bars or conduits during the drilling operation. Non-destructive testing and design drawings can be used to determine the locations of embedded items. Heavily reinforced structural members may not permit drilling, and these members should be strengthened by external techniques.

Space constraints from the outside of the member may not permit drilling holes transverse to the crack.

Do not install internal dowels in deteriorated concrete if the bond strength cannot be developed. The concrete strength must be evaluated for each installation.

Clean the drill holes of concrete dust prior to the installation of reinforcement and bonding agent. If the hole is not thoroughly cleaned, the bonding matrix will adhere to dust and a limited bond strength to the concrete will result.

5.2.4 *Installation details*—The pre-drilled holes should be drilled perpendicular to the crack or nearly so. A core bit or a solid drill bit may be used, but core bits create a smooth surface inside the hole. The smooth surface is less effective for bonding to the concrete. The embedment length on both sides of the crack must be sufficient to develop the required stress in the bar by bond strength. For epoxy bond, 10 to 15 times the reinforcing bar diameter is usually sufficient, but development lengths should be based on calculated design loads and bond stresses or on tests. For cement mortars, the
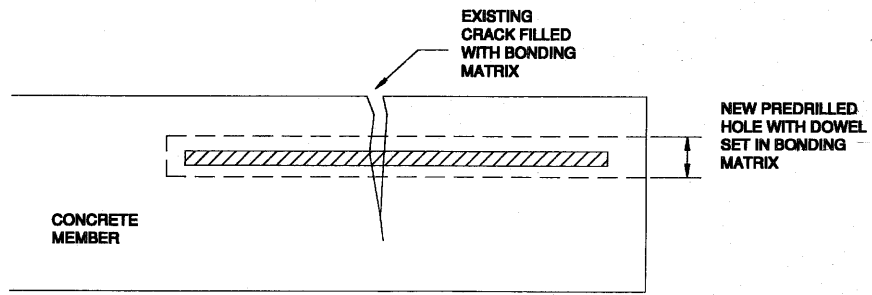
Fig. 5.1—Interior reinforcement provides increased tensile resistance normal to an existing crack when bonded in a predrilled hole or grove cut perpendicular to the crack
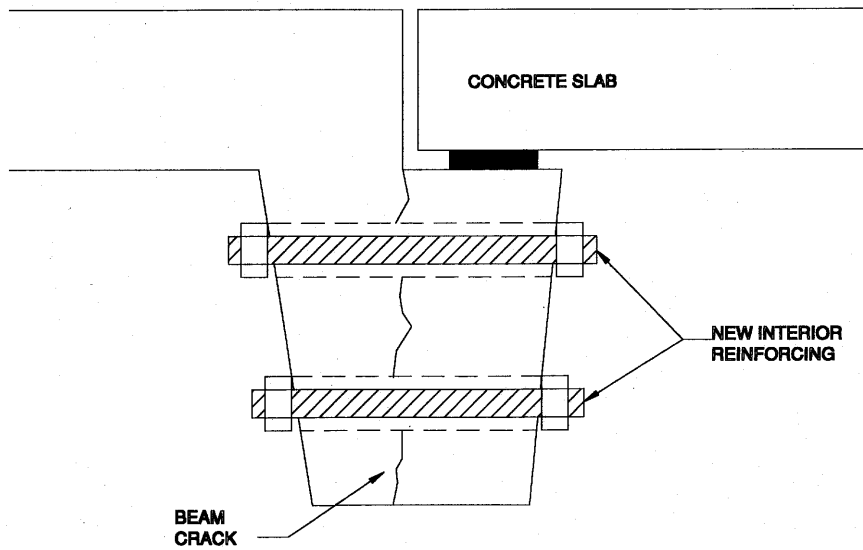
Fig. 5.2—Increasing flexural resistance with the addition of interior reinforcement bonded into predrilled hole
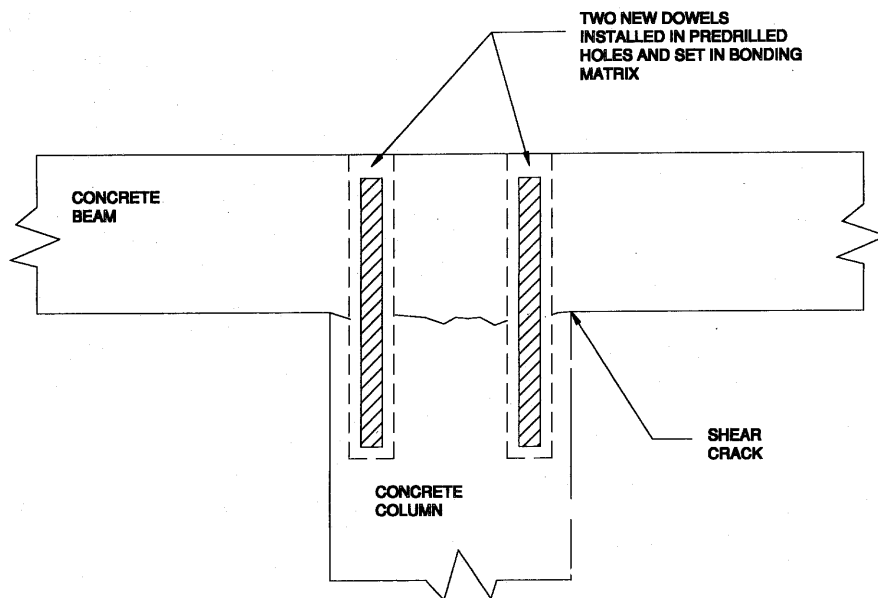
Fig. 5.3—Interior reinforcing for shear strengthening

development lengths given by ACI 318 are required. The final hole diameter should be from $^1/_8$ to $^1/_4$ in. (3 to 6 mm) larger than the dowel diameter if epoxy bonding agents are used. The hole diameter should be at least 2 in. (50 mm) larger than the bar for cement mortars. This provides an annular space that is adequate to allow for compaction of the mortar. However, epoxy viscosity is critical in selecting hole diameter for bar installation. Follow manufacturer's instructions and conduct trial installations in order to determine the best hole diameter and depth.

A vacuum and wire brush will clean the inside of drill holes sufficiently. Carbide tipped drills with internal vacuum ports are available to save time blowing out the hole after drilling. Install sufficient bonding agent into the hole to more than fill the annular space, or approximately half full if epoxy is used. Insert the dowel into the hole and displace the bonding agent. The viscosity of the bonding agent should be fluid enough to permit the agent to flow between the dowel and the hole.

5.2.5 *Example*—The Kansas Department of Transportation strengthened 84 reinforced concrete girder bridges as shown in Fig. 5.4 (Stratton and Crumpton, 1984; Stratton, Alexander, and Nolting, 1978 and 1982). The Kansas bridges had diagonal tension cracks in many of the girders of older two-lane, two-girder reinforced concrete structures. Calculations and exploratory programs beginning in about 1978 indicated that the load carrying capability of the bridges could be significantly enhanced by adding shear reinforcement in holes drilled diagonally. This procedure would not only repair the existing cracks but add diagonal tension strength to the members.

The procedure found most effective and used was the following:

1) Diagonal cracks on the surface of the girders were sealed with a silicone gel.
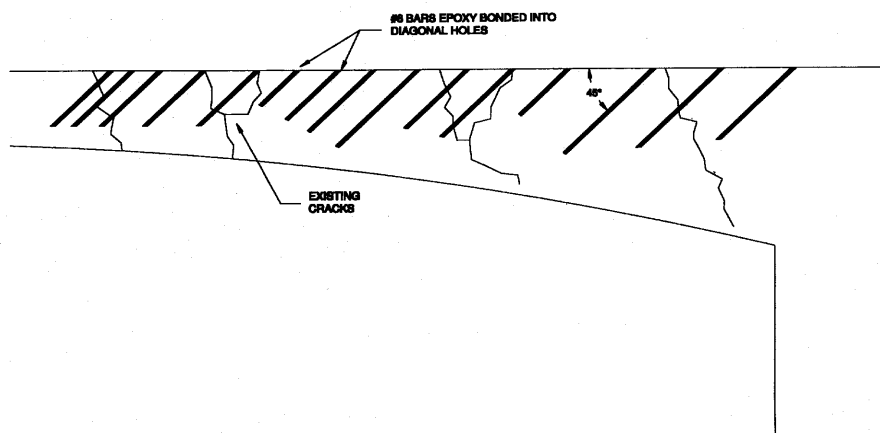

Fig. 5.4—Reinforced concrete girder of a Kansas bridge repaired and strengthened using reinforcing bars epoxy bonded into drilled holes (Stratton, Alexander, and Nolting, 1978)
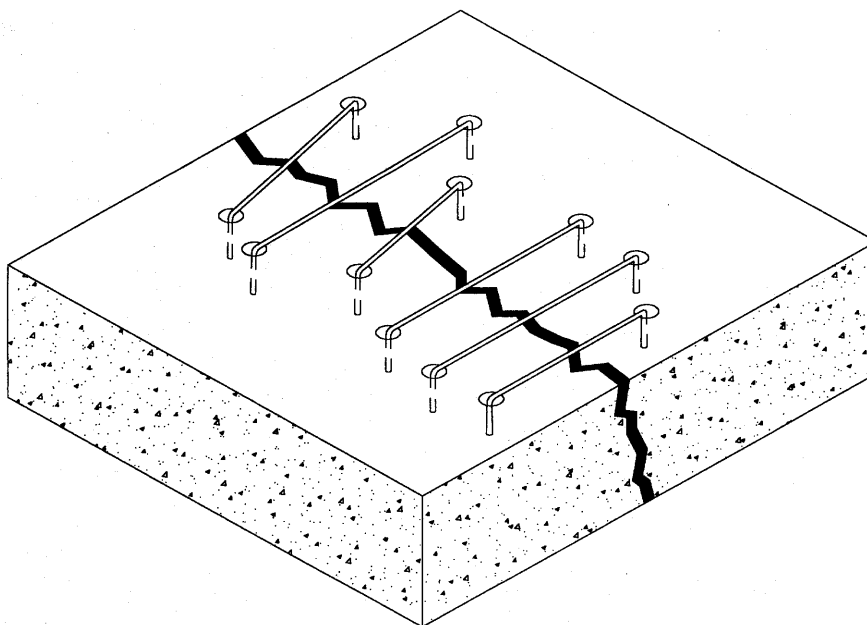

Fig. 5.5—External steel plate mechanically connected to damaged reinforced concrete beam for shear and/or flexural strengthening
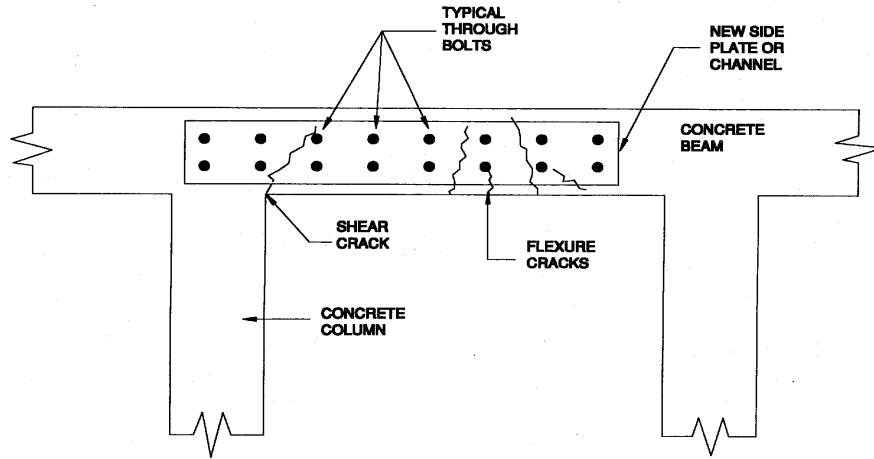
Fig. 5.6—Application of steel strapping to repair of 66 ft (20.1 m) long girders (Stratton, Alexander, and Nolting, 1982)
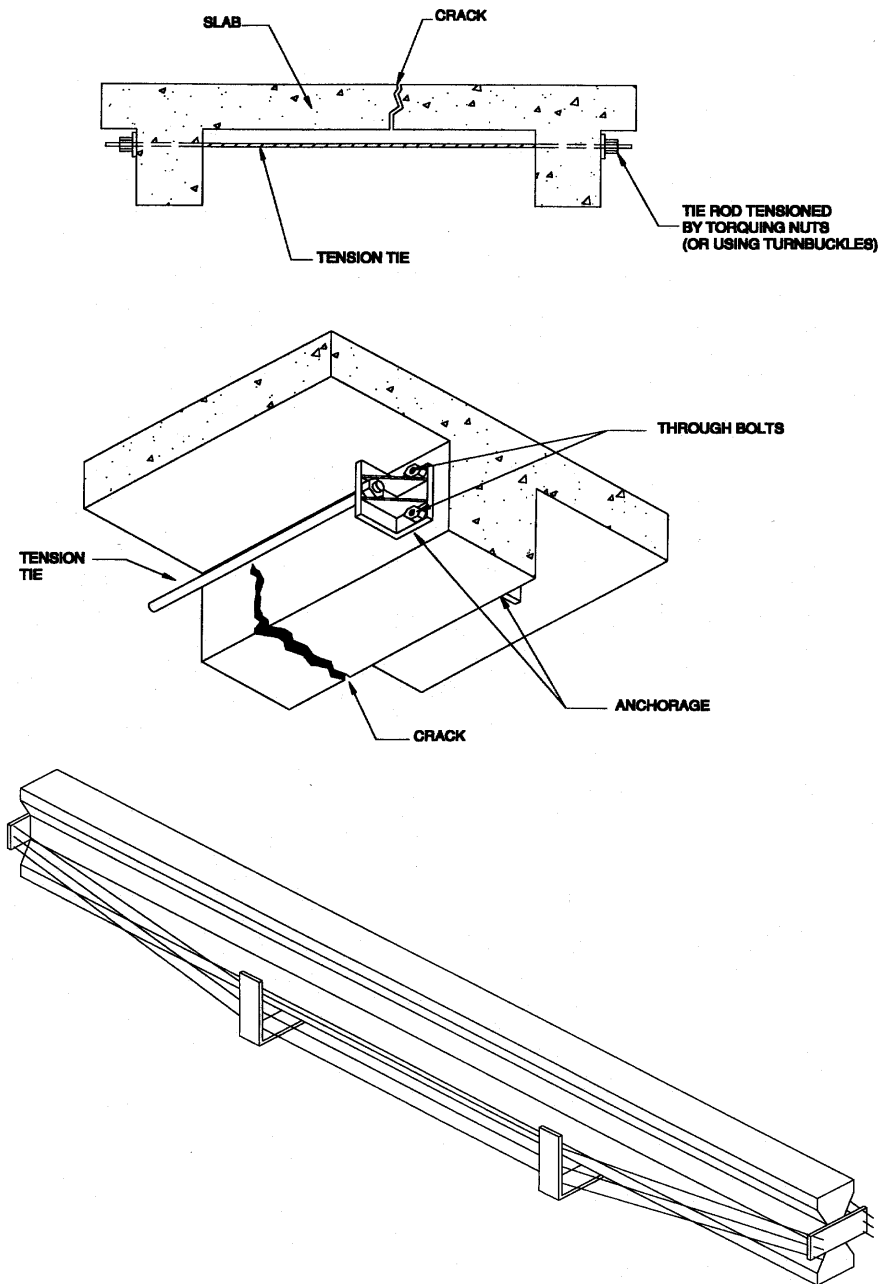

Fig. 5.7—External prestressing to close cracks and strengthen section

2) One in. (25 mm) diameter holes spaced about 14 in. (350 mm) apart along the length of the girder were drilled at a 45 degree angle on the centerline of each girder with a vacuum drill working from above.

3) Epoxy was pressure injected into the holes in order to fill the diagonal cracks and to nearly fill each hole.

4) A #6 deformed bar (19 mm dia) was inserted into the hole. The #6 bar was approximately 3 in. (75 mm) shorter than the full depth of the hole so that the top of the bar did not protrude out of the top of the hole.

In this reinforcing procedure, the bond between the steel reinforcement and the concrete was provided by the epoxy bond of the bar to the surrounding concrete after first repairing the concrete using epoxy injection.

Similar repair procedures were used on another project where about 800 concrete roof joists did not have adequate shear capacity. The structure was below grade, covered with backfill, and had an elastomeric waterproofing membrane and concrete protection slab on top of the roof slab. Drilling from the top was not feasible and the following repair procedure was used:

1) Cracks were injected with an epoxy adhesive.

2) Holes were drilled from the bottom of the joists upward at a 45 degree angle.

3) After cleaning, a two-component fast-setting adhesive resin in a pre-measured mylar cartridge was inserted into the hole.

4) A reinforcing bar with a specially designed threaded coupler was inserted in the hole while being rotated by a drill. The rotating bar broke apart the cartridge and mixed the two-component resin. The specially designed coupler prevented the resin from running out of the hole and held the bar in place until the adhesive hardened a few minutes later.

5) The threaded coupler was removed and the remaining shallow hole was patched.

5.3—Exterior reinforcing (encased and exposed)

5.3.1 *Description*—Steel elements may be placed on the exterior of an existing concrete member. The new reinforcement may be encased with shotcrete, mortar, plaster, or other product, or it may be left exposed and protected from corrosion with a coating. The reinforcement may be deformed bars, welded wire fabric, steel plate, steel rolled sections, steel strapping, or specially fabricated brackets. For members damaged by overload, erosion, abrasion, or chemical attack, the deteriorated or cracked concrete can be removed and new reinforcement installed around and adjacent to the remaining concrete. The new reinforcement is encased in conventionally placed concrete or in shotcrete. Where the existing concrete is in good condition, the new reinforcement may be bonded directly to the existing concrete surface after preparing the surface as described in Chapter 2. Epoxy and other chemical adhesives as well as portland cement concrete may be used to bond the new reinforcement or it may be mechanically fastened to the existing concrete.

5.3.2 *Advantages and typical uses*—Placement of exterior reinforcement may be the most convenient method for repair and strengthening where obstructions limit access of equipment needed for placement of interior reinforcement. If surface repair and placement of surface epoxy mortar, plaster, or shotcrete is required for concrete rehabilitation, placement of external reinforcement for strengthening may be accomplished in the same construction process.

External flexural, shear, and torsion reinforcement for beams and girders may be provided by bonding deformed reinforcing bars or plates to the surface of concrete girders with shotcrete, cast-in-place concrete, or epoxy and polymer concrete (Kajfasz, 1967; Toemsmeyer, 1981; Holman and Cook, 1984; Kahn, Townsend, and Kaldjian, 1975). Anchors may be required in the repair method to ensure composite action.

Steel plates may be attached to existing girders using bolts as illustrated in Fig. 5.5. Using a structural adhesive requires adequate surface preparation of both the steel and the concrete and selection of the appropriate adhesive to bond steel to concrete. Sandblasting of both the steel plate and concrete surface is the best method of preparation, but surface cleaning with solvents or high-pressure water blasting may be adequate for many cases.

Banding girders and columns with steel straps as shown in Fig. 5.6 is effective in increasing shear resistance (Lunoe and Willis, 1957; Kahn, 1980). The $1/2$ to 2 in. (13 to 50 mm) wide steel packaging bands are not bonded to the member, but their banding prestress effectively anchors each strap. Steel clamps bolted around an existing reinforced concrete member are also effective (Kahn, 1980).

Beams, girders, columns, and walls can be strengthened by placement of longitudinal reinforcing bars and stirrups or ties around the members and then encasing the members with shotcrete or cast-in-place concrete (Fratt, 1973; Davis, 1978; Strand, 1973). The shotcrete bonds the new reinforcement to the existing member. The added shotcrete also increases the size of the member and adds strength and stiffness. Consideration must be given to the additional dead weight of the member resulting from such additions.

Both masonry and reinforced concrete walls have been strengthened by adding surface layers of reinforcing bars or welded wire fabric and by application of shotcrete (Strand, 1973; Fratt, 1973; Kahn, 1984). The shotcrete bonds the new reinforcement to the wall. Often new dowels are embedded in holes drilled into perimeter columns and beams for a connection between the frame members and the strengthened, infilled shotcrete wall.

5.3.3 *Limitations*—Because the stiffness of repaired members is increased, load distribution in the structure is altered. Both repaired and unrepaired members including foundations should be checked for service load conditions.

External reinforcing always occupies space that was available for other uses before the repair.

Surface preparation of both steel and concrete is critical if bonding is required for composite action. Chapter 2 presents surface preparation techniques.

Careful consideration must be exercised when using structural adhesives, especially epoxy, due to their softening and loss of strength at elevated temperatures. Where required, appropriate fire protection must be provided.
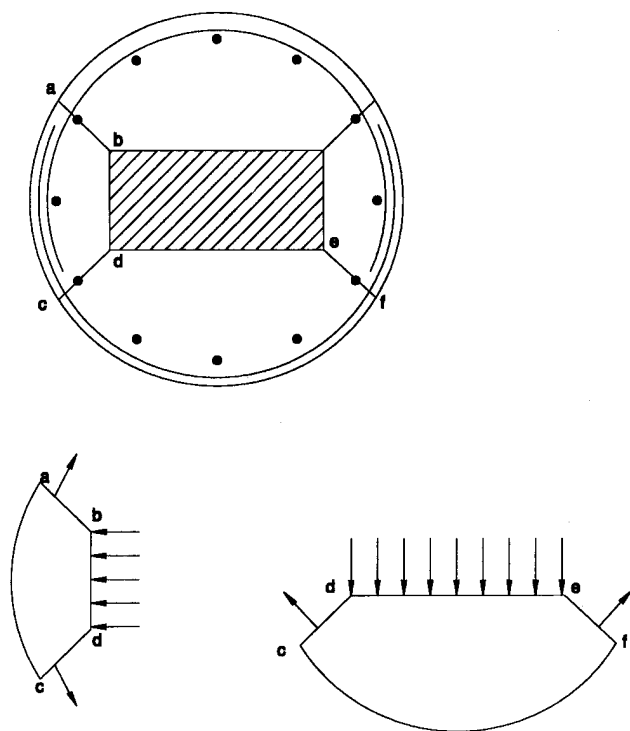
Fig. 5.8—Collar strengthening of a column (Klein and Gouwens, 1984)

5.3.4 *Examples*—The shear resistance of large reinforced concrete girders was increased with steel straps surrounding the girders (Lunoe and Willis, 1957). The 2 in. wide by 0.05 in. thick (50 x 1.3 mm) straps are identical to those used in material handling and packaging applications. The corners of the girders were protected with bent 16 gauge (1.5 mm thick) steel plates. The straps were then tensioned to a stress of approximately 42,000 psi (290 MPa); two seals were then crimped in place to secure the straps. Tests at the Portland Cement Association (PCA) (Elstner and Hogenstad, 1957) indicated that the shear resistance provided by the strap reinforcement can be predicted in the same manner as the strength provided by embedded stirrups. The PCA tests indicated that a prestress of about 25,000 psi (170 MPa) was necessary to ensure full efficiency of the banding straps.

The shear strength of reinforced concrete girders in a parking garage was increased by adding external stirrups encased in shotcrete. The repair procedure was as follows:

1) Side and bottom surfaces of beams were sandblasted to provide clean and rough surfaces.

2) New external stirrups consisting of pairs of U-shaped bars lapped together were placed around the existing beam. The horizontal section of the upper U-bar was placed in a slot cut into the top of the girder and vertical legs extended through holes cut in the slab.

3) The new stirrups were encased in shotcrete.

4) Shotcrete encasements were sounded to detect unbonded areas. Unbonded areas were removed and replaced.

5.4—Exterior post-tensioning

5.4.1 *Description*—Girders and slabs may be strengthened in both flexure and shear by addition of external tendons, rods, or bolts which are prestressed. Fig. 5.7 illustrates this external post-tensioning. The strands may be straight or harped.

5.4.2 *Advantages and typical uses*—The use of high-strength prestressing reinforcement effectively reduces the amount of reinforcement required in the repair and strengthening procedure. The prestressing also provides beam camber which helps to reduce deflection. The addition of a single post-tensioning arrangement increases both shear and flexural strength. The shear resistance is increased due to concrete compression and to the profile of the strands, and the flexural strength is increased due to the addition of longitudinal reinforcement.

5.4.3 *Limitations*—Placement and stressing of prestressing strands and rods is often difficult in congested buildings and interior locations. If positioning of hydraulic jacks is impossible or laborious, turn buckles or nuts on rods can be used to tension the steel.

Closing of cracks may not be possible because debris often collects in the open crack. As stressing progresses, debris and aggregates already in contact keep the crack open. Cleaning and filling the crack with epoxy or other appropriate material may be necessary prior to prestressing.

Providing adequate anchorage of the tendons is mandatory even though it may be difficult. Use of steel grillages on the far side of columns and at the end of beams (Fig. 5.7) is best because such anchorage uses bearing forces and because they permit stressing of the entire length of a member including end connections. Bolted or bonded side anchors may be an alternate anchorage. The anchors must be designed for the eccentric forces and the portion of the concrete members beyond the anchors must be checked for strength.

In indeterminate frames, post-tensioning induces secondary shear and moments which must be considered when planning the repair. Also, the new exposed post-tensioned strands will be visible, and may be distracting. Strands can be concealed in concrete or by cladding. Building codes should be checked for the installation of fireproofing on exposed reinforcing.

5.4.4 *Installation details*—The exterior post-tensioning method is performed with the same equipment and the same design criteria that all prestressing and post-tensioning projects require. The end plates must be properly designed, securely seated, and sufficient space must be provided for pulling the strands. Strand tensions are determined by design in accordance with ACI 318.

5.4.5 *Example*—Exterior post-tensioning was used to restore strength and serviceability of beams in a parking garage located in San Francisco (Aalami and Swanson, 1988). Two multi-strand tendons per beam were added, one on each side. New tendons were deflected down to the bottom of the beam at mid-span using specially designed hardware. The corrosion protection and fireproofing system around the new tendons consisted of a 2 in. (50 mm) diameter corrugated PVC pipe encased in a 6.5 in. (165 mm) square precast concrete tube. The
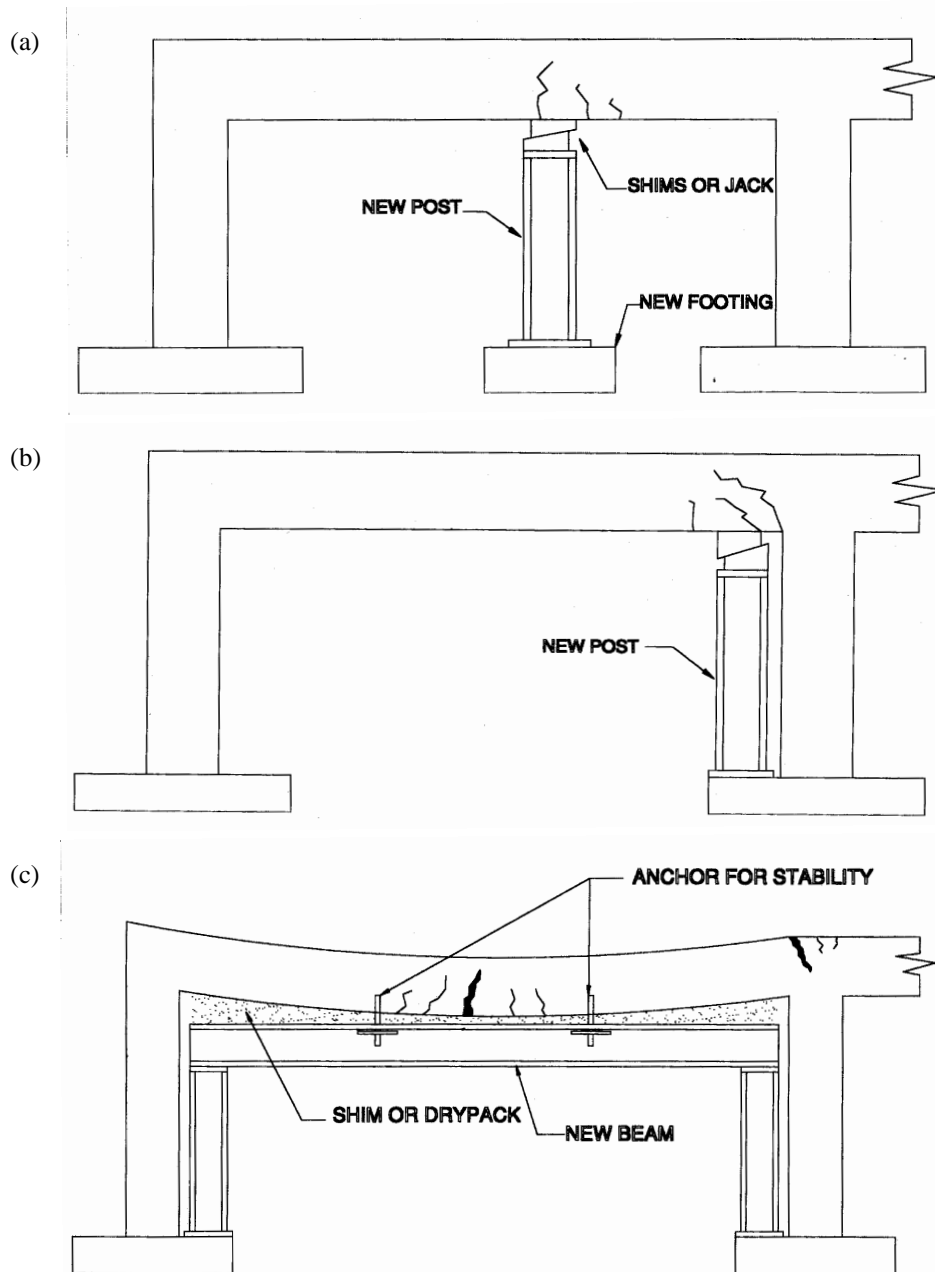
(a)

NEW POST

SHIMS OR JACK

NEW FOOTING

(b)

NEW POST

(c)

ANCHOR FOR STABILITY

SHIM OR DRYPACK

NEW BEAM

Fig. 5.9—Supplemental members

innovative repair design allowed the garage to remain fully operational during installation of the new tendons.

5.5—Jackets and collars

5.5.1 *Description*—Jacketing is the process whereby a section of an existing structural member is restored to original dimensions or increased in size by encasement in new portland cement or polymer-modified portland cement concrete. A steel reinforcement cage is constructed around the damaged section onto which shotcrete or cast-in-place concrete is placed.

Collars are jackets which surround only a part of a column or pier and typically are used to provide increased support to the slab or beam at the top of the column (Fig. 5.8).

The form for the jacket may be temporary or permanent and may consist of timber, corrugated metal, precast con-

crete, rubber, fiberglass, or special fabric, depending on the purpose and exposure. The jacket form is placed around the section to be repaired, creating an annular void between the jacket and the surface of the existing member. The form should be provided with spacers to assure equal clearance between it and the existing member.

A variety of materials including conventional concrete and mortar, epoxy mortar, grout, and latex-modified mortar and concrete have been used as encasement materials. Techniques for filling the jacket include pumping, tremie, or pre-placed aggregate concrete.

5.5.2 *Advantage and typical uses*—Jacketing is particularly applicable in repair of deteriorated columns, piers, and piling where all or a portion of the section to be repaired is under water. The method is applicable for protecting concrete, steel, and timber sections against further deterioration

as well as for strengthening. Permanent forms are advantageous in marine environments where added protection from weathering, abrasion, and chemical pollution is desired. Collars are effective in providing new capitals on existing columns for supporting slab floors (Klein and Gouwens, 1984). The collar provides increased shear capacity for the slab, and it decreases the effective length of the column. Collars may help satisfy architectural constraints better than jacketing the column for its full height.

5.5.3 *Limitations*—Both jackets and collars require that all deteriorated concrete be removed, cracks repaired, existing reinforcement be cleaned, and surfaces prepared. This preparation is required so that the newly placed materials will bond with the existing structure. Because jackets are often under water, such preparation is expensive and difficult. Nevertheless the applicability of jackets and collars is widespread and is generally cost-effective, especially if the alternative is replacement of the structure supported by the deteriorated member.

Jackets and collars occupy space that was available for other uses before repair.

5.5.4 *Installation details*—The forming techniques and the decision to use permanent or temporary forms are important details in jacketing. Timber or cardboard forms may be used as temporary or permanent forms. Corrugated steel forms are easy to assemble and are adequate temporary or permanent forms. Permanent fiberglass, rubber, and fabric forms have gained wide acceptance because they provide permanent resistance to chemical attack after the repair is complete. Additional information on jackets may be found in Chapter 3 of this guide.

5.6—Supplemental members

5.6.1 *Description*—Supplemental members are new columns, beams, or braces which are installed to support damaged structural members as illustrated in Fig. 5.9.

5.6.2 *Advantages and typical uses*—This repair method can be used if none of the other strengthening techniques is adequate for repair or if the structural configuration precludes use of other techniques. Supplemental members are quickly installed and therefore are suitable temporary emergency repair solutions. Typically new members are installed to support seriously cracked and deflected flexural members. Often, use of supplemental members may be the most economic alternative.

5.6.3 *Limitations*—Installing new columns or beams will restrict space within the repaired column bay. A new column will obstruct passage and new beams will reduce head room. Esthetically, the new beam or new column will be noticeable and distracting. Cross bracing or other means of providing resistance to lateral forces may be necessary if the original structure does not provide the necessary resistance. Such bracing further restricts interior space utilization. Loads and stresses in the existing structure may not be relieved unless special procedures are used.

The supplemental members may cause a redistribution of loads and forces that overstress an existing nearby member.

5.6.4 *Installation details*—The new supplemental members may be timber, steel, concrete, or masonry. The new members must be tightly shimmed, wedged, or anchored in position so that loads are transferred to the new members.

In Fig. 5.9(a) the new post supports a beam weak in flexural capacity. The new post requires adequate foundation support. The single span has become continuous so that negative and positive moment regions may be reversed. If cracking occurs in the new negative moment region, its acceptability must be considered.

Fig. 5.9(b) illustrates a post added to improve the shear resistance and to reduce the effective span of the existing beam. Often such posts added adjacent to the existing column are more economical than collars. The post may be positioned eccentrically on an existing footing which must then be analyzed to determine if its size or strength needs to be increased. In placing the post, a permanent jack, shims, or both may be required. The engineer must consider if jacking effectively redistributes dead loads to the new posts.

Fig. 5.9(c) illustrates placement of a supplemental beam beneath an existing deflected slab. The space between the new beam and existing structure must be shimmed or dry packed. To provide lateral stability to the supplemental member, it may be necessary to mechanically anchor it to the existing slab and/or columns. If the existing slab is supported on beams, the new beam could be supported on the existing beams instead of new posts.

5.6.5 *Example*—A reinforced concrete multi-story condominium suffered severe shear and flexural cracking in the second story girders. The girders supported a lobby area over a parking level. Because parking access would not be adversely affected, steel columns were shimmed into position beneath many girders. Small reinforced concrete spread footings were located beneath the new columns.

CHAPTER 6—REFERENCES
6.1—Specified and/or recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

American Association of State Highway and Transportation Officials

T 259   Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration

American Concrete Institute

201.2R   Guide to Durable Concrete

211.1   Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete

222R   Corrosion of Metals in Concrete

223   Standard Practice for the Use of Shrinkage-Compensating Concrete

234R   Guide for the Use of Silica Fume in Concrete

304R   Guide for Measuring, Mixing, Transporting, and Placing Concrete

304.1R Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications

305R Hot Weather Concreting

306R Cold Weather Concreting

306.1 Standard Specification for Cold Weather Concreting

308 Standard Practice for Curing Concrete

318 Building Code Requirements for Structural Concrete

355.1R State-of-the-Art Report on Anchorage to Concrete

439.3R Mechanical Connections of Reinforcing Bars

503R Use of Epoxy Compounds with Concrete

503.4 Standard Specifications for Repairing Concrete with Epoxy Mortars

504R Guide to Sealing Joints in Concrete Structures

506R Guide to Shotcrete

506.1R State-of-the-Art Report on Fiber Reinforced Shotcrete

506.2 Specification for Materials, Proportioning, and Application of Shotcrete

506.3R Guide to Certification of Shotcrete Nozzlemen

515.1R Guide to the Use of Waterproofing, Dampproofing, Protective, and Decorative Barrier Systems for Concrete

544.3R Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete

544.4R Design Considerations for Steel Fiber Reinforced Concrete

548R Polymers in Concrete

548.1R Guide for the Use of Polymers in Concrete

548.3R State-of-the-Art Report on Polymer Modified Concrete

548.4 Standard Specification for Latex-Modified Concrete

549R State-of-the-Art Report on Ferrocement

American Society for Testing and Materials

B 117 Test Method of Salt Spray (Fog) Testing

C 33 Specification for Concrete Aggregates

C 67 Test Methods of Sampling and Testing Brick and Structural Clay Tile

C 94 Specification for Ready-Mixed Concrete

C 150 Specification for Portland Cement

C 267 Test Method for Chemical Resistance of Mortars

C 387 Specification for Packaged, Dry, Combined Materials for Mortar and Concrete

C 642 Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete

C 672 Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals

C 685 Specification for Concrete Made by Volumetric Batching and Continuous Mixing

C 711 Test Method for Low-Temperature Flexibility and Tenacity of One-Part, Elastomeric, Solvent-Release Type Sealants

C 806 Test Method for Restrained Expansion of Expansive Cement Mortar

C 836 Specification for High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane for Use with Separate Wearing Course

C 845 Specification for Expansive Hydraulic Cement

C 878 Test Method for Restrained Expansion of Shrinkage-Compensating Concrete

C 881 Specification for Epoxy-Resin-Base Bonding Systems for Concrete

C 928 Specification for Packaged, Dry, Rapid-Hardening Cementitious Materials for Concrete Repairs

C 937 Specification for Grout Fluidifier for Preplaced-Aggregate Concrete

C 938 Practice for Proportioning Grout Mixtures for Preplaced-Aggregate Concrete

C 1059 Specification for Latex Agents for Bonding Fresh to Hardened Concrete

C 1107 Specification for Packaged Dry Hydraulic-Cement Grout (Nonshrink)

C 1116 Specification for Fiber-Reinforced Concrete and Shotcrete

C 1202 Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

C 1240 Specification for Silica Fume for Use in Hydraulic-Cement Concrete and Mortar

D 56 Test Method for Flash Point by Tag Closed Tester

D 93 Test Methods for Flash Point by Pensky-Martens Closed Tester

D 412 Test Methods for Vulcanized Rubber and Thermoplastic Rubbers and Thermoplastic Elastomers—Tension

D 429 Test Method for Rubber Property—Adhesion to Rigid Substrates

D 522 Test Methods for Mandrel Bend Test of Attached Organic Coatings

D 523 Test Method for Specular Gloss

D 1353 Test Method for Nonvolatile Matter in Volatile Solvents for Use in Paint, Varnish, Lacquer, and Related Products

D 1474 Test Methods for Indentation Hardness of Organic Coatings

D 1475 Test Method for Density of Paint, Varnish, Lacquer, and Related Products

D 1640 Test Methods for Drying, Curing, or Film Formation of Organic Coatings at Room Temperature

D 1642 Test Methods for Elasticity or Toughness of Varnishes

D 1647 Test Method for Resistance of Dried Films of Varnishes to Water and Alkali

D 1653 Test Method for Water Vapor Transmission of Organic Coating Films

D 2047 Test Method for Static Coefficient of Friction of Polish-Coated Floor Surfaces as Measured by the James Machine

D 2134 Test Method for Determining the Hardness of Organic Coatings with a Sward-Type Hardness Rocker

D 2196 Test Method for Rheological Properties of Non-Newtonian Materials by Rotational (Brookfield) Viscometer

D 2197 Test Methods for Adhesion of Organic Coatings by Scrape Adhesion Tester

D 2240 Test Method for Rubber Property—Durometer Hardness

D 2247 Practice for Testing Water Resistance of Coatings in 100% Relative Humidity

D 2370 Test Method for Tensile Properties of Organic Coatings

D 2620 Test Method for Light Stability of Clear Coatings

D 2794 Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact)

D 3273 Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber

D 3274 Test Method of Evaluating Degree of Surface Disfigurement of Paint Films by Microbial (Fungal or Algal) Growth or Soil and Dirt Accumulation

D 3278 Test Method for Flash Point of Liquids by Setaflash-Closed-Cup Apparatus

D 3359 Test Methods for Measuring Adhesion by Tape Test

D 3363 Test Method for Film Hardness by Pencil Test

D 3456 Practice for Determining by Exterior Exposure Tests Susceptibility of Paint Films to Microbiological Attack

D 4138 Test Method for Measurement of Dry Film Thickness of Protective Coating Systems by Destructive Means

D 4141 Practice for Conducting Accelerated Outdoor Exposure Tests for Coatings

D 4214 Test Methods for Evaluating Degree of Chalking of Exterior Paint Films

D 4541 Method for Pull-Off Strength of Coatings Using Portable Adhesion-Testers

E 84 Test Method for Surface Burning Characteristics of Building Materials

E 96 Test Methods for Water Vapor Transmission of Materials

E 514 Test Method of Water Permeance of Masonry

G 26 Practice for Operating Light Exposure Apparatus (Xenon-Arc Type) With and Without Water for Exposure of Nonmetallic Materials

American Welding Society

D1.4 Structural Welding Code—Reinforcing Steel

NSF International

NSF 61 Drinking Water System Components—Health Effects

These publications may be obtained from the following organizations:

American Association of State Highway and Transportation Officials
444 North Capitol Street NW, Suite 225
Washington, DC 20001

American Concrete Institute
P. O. Box 9094
Farmington Hills, MI 48333

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959

American Welding Society
P. O. Box 351040
Miami, FL 33135

NSF International
P. O. Box 130140
Ann Arbor, MI 48113-0140

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