

Chapter 4 Planning and Design of Concrete Repairs

4-1. General Considerations

To achieve durable repairs it is necessary to consider the factors affecting the design and selection of repair systems as parts of a composite system. Selection of a repair material is one of the many interrelated steps; equally important are surface preparation, the method of application, construction practices, and inspection. The critical factors that largely govern the durability of concrete repairs in practice are shown in Figure 4-1. These factors must be considered in the design process so that a repair material compatible with the existing concrete substrate can be selected. Compatibility is defined as the balance of physical, chemical, and electrochemical properties and dimensions between the repair material and the concrete

substrate. This balance is necessary if the repair system is to withstand all anticipated stresses induced by volume changes and chemical and electrochemical effects without distress or deterioration in a specified environment over a designated period of time. For detailed discussions of compatibility issues and the need for a rational approach to durable concrete repairs, see Emmons, Vaysburd, and McDonald (1993 and 1994).

Dimensional compatibility is one of the most critical components of concrete repair. Restrained contraction of repair materials, the restraint being provided through bond to the existing concrete substrate, significantly increases the complexity of repair projects as compared to new construction. Cracking and debonding of the repair material are often the result of restrained contractions caused by volume changes. Therefore, the specified repair material must be dimensionally compatible with the existing concrete substrate to minimize the potential for failure. Those material properties that influence dimensional

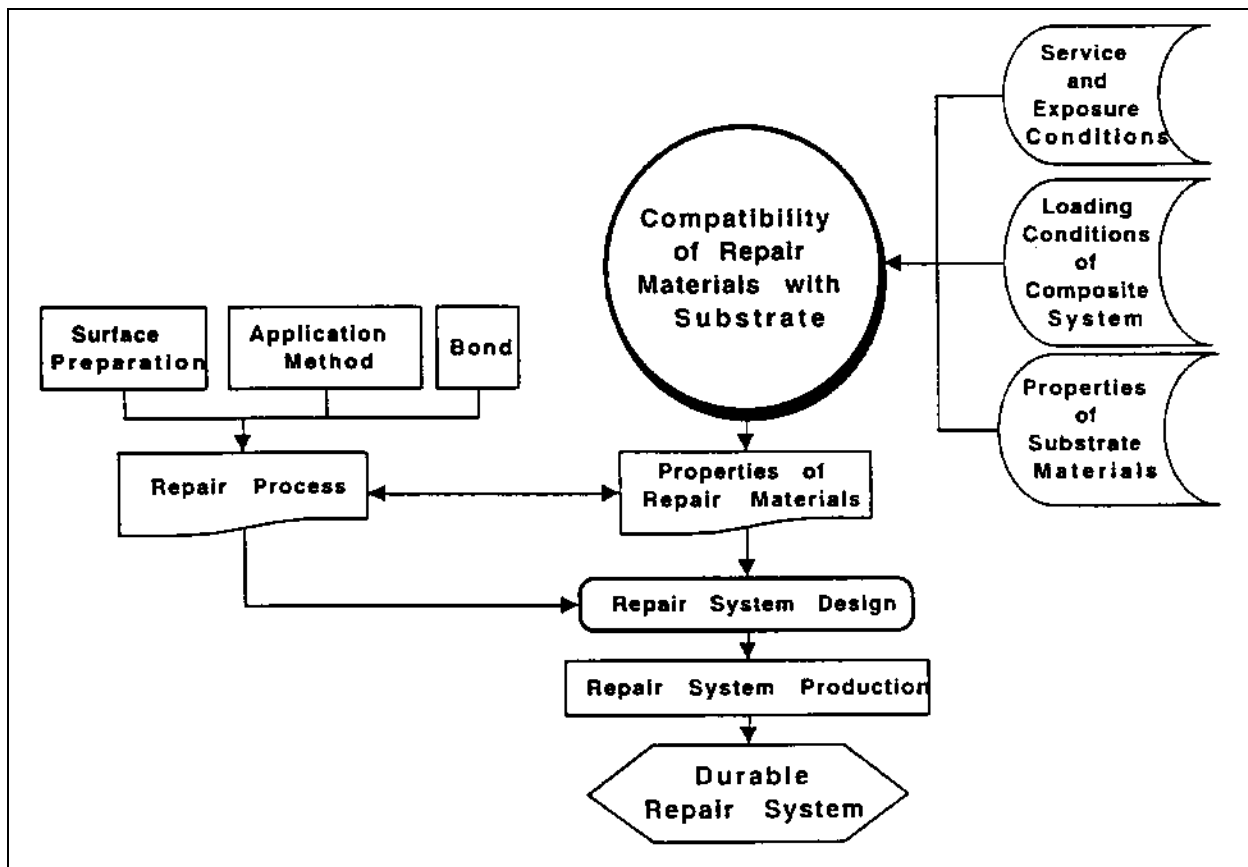


Figure 4-1. Factors affecting the durability of concrete repair systems (Emmons and Vaysburd 1995)

compatibility include drying shrinkage, thermal expansion, modulus of elasticity, and creep.

4-2. Properties of Repair Materials

In addition to conventional portland-cement concrete and mortar, there are hundreds of proprietary repair materials on the market, and new materials are continually being introduced. This wide variety of both specialty and conventional repair materials provides a greater opportunity to match material properties with specific project requirements; however, it can also increase the chances of selecting an inappropriate material. No matter how carefully a repair is made, use of the wrong material will likely lead to early repair failure (Warner 1984). Some of the material properties and their relative importance to durable repairs are discussed in the following text. These properties should be considered before any material is selected for use on a repair or rehabilitation project.

a. Compressive strength. Although there is some controversy over the required structural performance for many repairs, it is generally accepted that the repair material should have a compressive strength similar to that of the existing concrete substrate. Assuming the need for repair is not necessitated by inadequate strength, there is usually little advantage to be gained from repair materials with compressive strengths greater than that of the concrete substrate. In fact, significantly higher strengths of cementitious materials may indicate an excessive cement content which can contribute to higher heat of hydration and increased drying shrinkage. Repair of erosion-damaged concrete is one area in which increased strength (and corresponding higher erosion resistance) of the repair material is desirable.

b. Modulus of elasticity. Modulus of elasticity is a measure of stiffness with higher modulus materials exhibiting less deformation under load compared to low modulus materials. In simple engineering terms, the modulus of elasticity of a repair material should be similar to that of the concrete substrate to achieve uniform load transfer across the repaired section. A repair material with a lower modulus of elasticity will exhibit lower internal stresses thus reducing the potential for cracking and delamination of the repair.

c. Coefficient of thermal expansion. All materials expand and contract with changes in temperature. For a given change in temperature, the amount of expansion or contraction depends on the coefficient of thermal expansion for the material. Although the coefficient of expansion of conventional concrete will vary somewhat,

depending on the type of aggregate, it is usually assumed to be about 10.8 millionths per degree C (6 millionths per degree F). Using repair materials such as polymers, with higher coefficients of expansion, will often result in cracking, spalling, or delamination of the repair.

(1) Depending on the type of polymer, the coefficient of expansion for unfilled polymers is 6 to 14 times greater than that for concrete. Adding fillers or aggregate to polymers will improve the situation, but the coefficient of expansion for the polymer-aggregate combinations will still be one and one-half to five times that of concrete. As a result, the polymer repair material attempts to expand or contract more than the concrete substrate. This movement, when restrained through bond to the existing concrete, induces stresses that can cause cracking as the repair material attempts to contract or buckling and spalling when the repair material attempts to expand.

(2) While thermal compatibility is most important in environments that are frequently subject to large temperature changes, it should also be considered in environments in which temperature changes are not as frequent. Also, thermal compatibility is especially important in large repairs and/or overlays.

d. Adhesion/bond. In most cases, good bond between the repair material and the existing concrete substrate is a primary requirement for a successful repair. Bond strengths determined by slant-shear tests (ASTM C 882) are often reported by material suppliers. However, these values are highly dependent on the compressive strength of the substrate portion of the test cylinder. The test procedure requires only a minimum compressive strength of 31 MPa (4,500 psi) with no maximum strength. Therefore, these values have little or no value in comparing alternate materials unless the tests were conducted with equal substrate strengths.

(1) Bond is best specified as a surface preparation requirement. The direct tensile bond test described in ACI 503R is an excellent technique for evaluating materials, surface preparation, and placement procedures. A properly prepared, sound concrete substrate will almost always provide sufficient bond strength. In many cases, bond failures between repair materials and a properly prepared concrete substrate are a result of differential thermal strains or drying shrinkage and are not a result of inadequate bond strengths.

(2) According to ACI 503.5R, polymer adhesives provide a better bond of plastic concrete to hardened concrete than can be obtained with a cement slurry or the

plastic concrete alone. However, experience indicates that the improvement in bond is less than 25 percent as compared to properly prepared concrete surfaces without adhesives.

e. Drying shrinkage. Since most repairs are made on older structures where the concrete will exhibit minimal, if any, additional drying 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 w/c or by using construction procedures that minimize the shrinkage potential. Examples include dry-pack and preplaced-aggregate concrete. However, proprietary materials are being used in many repairs, often with undesirable results.

(1) A random survey of data sheets for cement-based repair materials produced in this country showed that drying shrinkage data was not even reported by some manufacturers. In those cases where data was reported, manufacturers tended to use a variety of tests and standards to evaluate the performance of their products. This arbitrary application and modification of test methods has resulted in controversy and confusion in the selection and specification of repair materials. Consequently, a study was initiated, as part of the REMR research program, to select a reliable drying shrinkage test and to develop performance criteria for selecting cement-based repair materials (Emmons and Vaysburd 1995).

(a) Three test methods are currently being evaluated in laboratory and field studies: ASTM C 157 (Modified); Shrinkage Cracking Ring; and German Angle Method. The ASTM test method, with modified curing conditions and times for length change measurements, has been used to develop preliminary performance criteria for drying shrinkage. In the modified procedure, materials are mixed and cured for 24 hr in accordance with manufacturer's recommendations. When no curing is recommended, specimens are cured in air at 50 percent relative humidity. When damp curing is recommended, specimens are placed in a moist curing room. No curing compounds are used. Following the 24 hr curing period, specimens are stored in air at 50 percent relative humidity with length change measurements at 1, 3, 28, and 60 days after casting.

(b) The ASTM C 157 (Modified) test method has been used to evaluate the drying shrinkage of 46 commercially available patching materials (Gurjar and Carter 1987). Test results at 28 days were sorted and categorized by Emmons and Vaysburd (in preparation) as shown in Figure 4-2. Shrinkage of conventional concrete

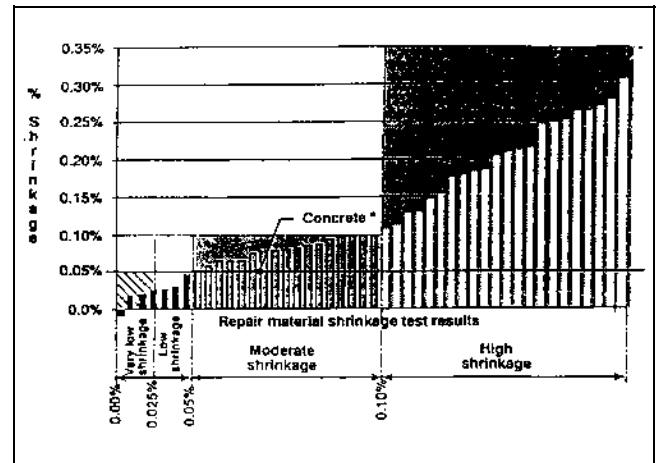


Figure 4-2. Classification of repair materials based on drying shrinkage (Emmons and Vaysburd 1995)

(0.05 percent at 28 days) was selected as a benchmark. Eighty-five percent of the materials tested had a higher shrinkage than that of concrete.

(2) Based on this work, a maximum shrinkage of 0.04 percent at 28 days (ASTM C 157 (modified)) has been proposed as preliminary performance criteria for dimensionally compatible repair materials. Final performance criteria will be selected upon completion of current large-scale laboratory and field tests to establish a correlation between laboratory test results and field performance.

f. Creep. In structural repairs, creep of the repair material should be similar to that of the concrete substrate, whereas in protective repairs higher creep can be an advantage. In the latter case, stress relaxation through tensile creep reduces the potential for cracking. It is unfortunate that most manufacturers make no mention of creep in their literature and are unable to supply basic values or to advise on environmental effects. Current tensile and compressive creep tests on selected repair materials should provide some insight into the role of creep in the overall repair system.

g. Permeability. Good quality concrete is relatively impermeable to liquids, but when moisture evaporates at a surface, replacement liquid is pulled to the evaporating surface by diffusion. If impermeable materials are used for large patches, overlays, or coatings, moisture that diffuses through the base concrete can be trapped between the substrate and the impermeable repair material. The

entrapped moisture can cause failure at the bond line or critically saturate the substrate and, in the case of nonair-entrained concrete, can cause the substrate to fail if it is subjected to repeated cycles of freezing and thawing. Entrapped moisture can be a particularly troublesome problem with Corps hydraulic structures that are subject to freezing and thawing. Materials with low water absorption and high water vapor transmission characteristics are desirable for most repairs.

4-3. Application and Service Conditions

The conditions under which the repair material will be placed and the anticipated service or exposure conditions can have a major impact on design of a repair and selection of the repair material. The following factors should be considered in planning a repair strategy (Warner 1984).

a. Application conditions.

(1) Geometry. The depth and orientation of a repair section can influence selection of the repair material. In thick sections, heat generated during curing of some repair materials can result in unacceptable thermal stresses. Also, some materials shrink excessively when placed in thick layers. Some materials, particularly cementitious materials, will spall if placed in very thin layers. In contrast, some polymer-based materials can be placed in very thin sections. The maximum size of aggregate that can be used will be dictated by the minimum thickness of the repair. The repair material must be capable of adhering to the substrate without sagging when placed on vertical or overhead surfaces without forming.

(2) Temperature. Portland-cement hydration ceases at or near freezing temperatures, and latex emulsions will not coalesce to form films at temperature below about 7 °C (45 °F). Other materials may be used at temperatures well below freezing, although setting times may be increased. High temperatures will make many repair materials set faster, decrease their working life, or preclude their use entirely.

(3) Moisture. A condition peculiar to hydraulic structures is the presence of moisture or flowing water in the repair area. Generally, flowing water must be stopped by grouting, external waterproofing techniques, or drainage systems prior to repair. Some epoxy and polymer materials will not cure properly in the presence of moisture while others are moisture insensitive. Materials suitable for spall repair of wet concrete surfaces have been identified by Best and McDonald (1990a).

(4) Location. Limited access to the repair site may restrict the type of equipment, and thus the type of material that can be used for repair. Also, components of some repair materials are odorous, toxic, or combustible. Obviously, such materials should not be used in poorly ventilated areas or in areas where flammable materials aren't permitted.

b. Service conditions.

(1) Downtime. Materials with rapid strength gain characteristics that can be easily placed with minimal waste should be used when the repaired structure must be returned to service in a short period of time. Several types of rapid-hardening cements and patching materials are described in REMR Technical Note CS-MR-7.3 (USAEWES 1985g).

(2) Traffic. If the repair will be subject to heavy vehicular traffic, a high-strength material with good abrasion and skid resistance is necessary.

(3) Temperature. A material with a coefficient of thermal expansion similar to that of the concrete substrate should be used for repairs subject to wide fluctuations in temperature. High-service temperatures may adversely affect the performance of some polymer materials. Resistance to cycles of freezing and thawing will be very important in many applications.

(4) Chemical attack. Acids and sulfates will cause deterioration in cement-based materials while polymers are resistant to such chemical attack. However, strong solvents may attack some polymers. Soft water is corrosive to portland-cement materials.

(5) Appearance. If it is necessary to match the color and texture of the original concrete, many, if not most, of the available repair materials will be unsuitable. Portland-cement mixtures with materials and proportions similar to those used in the original construction are necessary where appearance is a major consideration. Procedures for repair of architectural concrete are described by Dobrowolski and Scanlon (1984).

(6) Service life. The function and remaining service life of the structure requiring repair should be considered in selection of a repair material. An extended service life requirement may dictate the choice of repair material regardless of cost. On the other hand, perhaps a lower cost, less durable, or more easily applied material can be used if the repair is only temporary.

4-4. Material Selection

Most repair projects will have unique conditions and special requirements that must be thoroughly examined before the final repair material criteria can be established. Once the criteria for a dimensionally compatible repair have been established, materials with the properties necessary to meet these criteria should be identified. A variety of repair materials have been formulated to provide a wide range of properties. Since these properties will affect the performance of a repair, selecting the correct material for a specific application requires careful study. Properties of the materials under consideration for a given repair may be obtained from manufacturer's data sheets, the REMR Repair Materials Database and *The REMR Notebook* (USAEWES 1985), evaluation reports, contact with suppliers, or by conducting tests.

a. Material properties.

(1) Manufacturer's data. Values for compressive strength, tensile strength, slant-shear bond, and modulus of elasticity are frequently reported in material data sheets provided by suppliers. However, other material properties of equal or greater importance, such as drying shrinkage, tensile bond strength, creep, absorption, and water vapor transmission, may not be reported.

(a) Experience indicates that the material properties reported in manufacturer's data sheets are generally accurate for the conditions under which they were determined. However, the designer should beware of those situations in which data on a pertinent material property is not reported. Unfavorable material characteristics are seldom reported.

(b) Material properties pertinent to a given repair should be requested from manufacturers if they are not included in the data sheets provided. General descriptions of materials, such as compatible, nonshrink, low shrinkage, etc., should be disregarded unless they are supported by data determined in accordance with standardized test methods. Material properties determined in accordance with "modified" standard tests should be viewed with caution, particularly if the modifications are not described.

(2) Repair Material Database. The REMR Repair Materials Database is described in Section 4-5. The computerized database provides rapid access to the results of tests conducted by the Corps and others; however, less than 25 percent of the available repair materials have been evaluated to date. *The REMR Notebook* currently contains 128 Material Data Sheets that include material

descriptions, uses and limitations, available specifications, manufacturer's test results, and Corps test results. In addition, *The REMR Notebook* contains a number of Technical Notes that describe materials and procedures that can be used for maintenance and repair of concrete.

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

(4) Conduct tests. The formulations for commercially available materials are subject to frequent modifications for a number of reasons including changes in ownership, changes in raw materials, and new technology. Sometimes these modifications result in changes in material properties without corresponding changes to the manufacturer's data sheets or notification by the material supplier. Consequently, testing of the repair material is recommended to ensure compliance with design criteria if durability of the repair is of major importance, or the volume of repair is large (Krauss 1994).

b. Selection considerations. Concrete repair materials have been formulated to provide a wide range of properties; therefore, it is likely that more than one type of material will satisfy the design criteria for durable repair of a specific structure. In this case, other factors such as ease of application, cost, and available labor skills and equipment should be considered in selection of the repair material. To match the properties of the concrete substrate as closely as possible, portland-cement concrete or similar cementitious materials are frequently the best choices for repair. There are some obvious exceptions such as repairs that must be resistant to chemical attack. However, an arbitrary decision to repair like with like will not necessarily ensure a durable repair: The new repair material must be dimensionally compatible with the existing substrate, which has often been in place for many years.

4-5. Repair Materials Database

The Corps of Engineers Repair Material Database was developed to provide technology transfer of results from evaluations of commercial repair products performed under the REMR Research Program. The database contains manufacturer's information on uses, application procedures, limitations and technical data for approximately 1,860 commercially available repair products. In addition, Corps of Engineers test results are included for

280 products and test results from other sources for 120 products. Results of material evaluations performed by the Corps of Engineers are added to the database as reports are published. Database organization and access procedures are described in detail by Stowe and Campbell (1989) and summarized in the following.

a. Access. The database is maintained on a host computer that can be accessed by telephone via a modem using the following communication parameters:

Baud Rate: 1,200 to 9,600	Emulation: VT-100
Data Bits: 8	Stop Bits: 1
Phone No.: (601) 634-4223	Parity: None

b. Operation.

(1) The database is menu driven and has help windows to facilitate its use. The products in the database are identified as either end-use or additive. An end-use product is a material that is used as purchased to make a repair, whereas an additive product is a material used in combination with other materials to produce an end-use product. The end-use products portion of the database contains products for maintenance and repair of concrete, steel, or both. The additive products portion of the database contains products that are portland-cement admixtures, binders, fibers, or special filler materials.

(2) For end-use products, product categories identify the basic type of material of which the product is composed, and for additive products, the type of end-use product for which the product is an ingredient or additive. The product uses identify the type use(s) for which the product is applicable. Keywords for searching category and use fields can be listed through the program help screens along with their definitions. Once the user selects the end-use or additive database, searches can be made by manufacturer's name, product name, product category, product use, or both category and use.

c. Assistance. For assistance or additional information regarding the database contact:

CEWES-SC-CA
 3909 Halls Ferry Road
 Vicksburg, MS 39180-6199
 Phone: (601) 634-2814

4-6. General Categorization of Repair Approach

For ease of selecting repair methods and materials, it is helpful to divide the possible approaches into two general

categories: those more suited for cracking or those more suited for spalling and disintegration. This categorization requires that some of the symptoms that were listed in Table 2-1 be regrouped as follows to facilitate selection of a repair approach:

<u>Cracking</u> <u>Repair Approaches</u>	<u>Spalling and Disintegration</u> <u>Repair Approaches</u>
Construction faults (some)	Construction faults (some)
Cracking	Disintegration
Seepage	Erosion
	Spalling

Note that distortion or movement and joint sealant failures, which were listed in Table 2-1, are not included in these categories. These are special cases that must be handled outside the process to be outlined in this chapter. Joint repair and maintenance are covered in Chapter 7. Distortion and movement are usually indications of settlement or of chemical reactions causing expansion of concrete such as severe alkali-aggregate reaction. Repairs for these conditions are beyond the scope of this manual. Materials and methods more suited for crack repairs are described in Section 4-7, while those more suited for spalling and disintegration repairs are described in Section 4-8.

4-7. Repair of Cracking

The wide variety of types of cracking described in Chapter 2 suggests that there is no single repair method that will work in all instances. A repair method that is appropriate in one instance may be ineffective or even detrimental in another. For example, if a cracked section requires tensile reinforcement or posttensioning to be able to carry imposed loads, routing and sealing the cracks with a sealer would be ineffective. On the other hand, if a concrete section has cracked because of incorrect spacing of contraction joints, filling the cracks with a high-strength material such as epoxy will only cause new cracking to occur as the concrete goes through its next contraction cycle.

a. Considerations in selecting materials and methods. Prior to the selection of the appropriate material and method for repair of cracking, the following questions should be answered (Johnson 1965):

(1) What is the nature of the cracking? Are the cracks in pattern or isolated? What is the depth of the cracking? Are the cracks open or closed? What is the extent of the cracking?

(2) What was the cause of the cracking?

(3) What was the exact mechanism of the cracking? This question requires that an analysis beyond the simple identification of the cause be conducted. For example, if the cause of the cracking has been determined to be drying shrinkage, it should then be determined whether the occurrence is the result of unusual restraint conditions or excess water content in the concrete. Understanding the mechanism will help to ensure that the same mistake is not repeated.

(4) Is the mechanism expected to remain active? Whether the causal mechanism is or is not expected to remain active will play a major role in the process to select a repair material and method.

(5) Is repair feasible? Repair of cracking caused by severe alkali-aggregate reaction may not be feasible.

(6) Should the repair be treated as spalling rather than cracking? If the damage is such that future loss of concrete mass is probable, treatment of the cracks may not be adequate. For example, cracking caused by corrosion of embedded metal or by freezing and thawing would be best treated by removal and replacement of concrete rather than by one of the crack repair methods.

(7) What will be the future movement of the crack? Is the crack active or dormant? The repair materials and techniques for active cracks are much different from the

repair materials and techniques for dormant cracks. Many cracks which are still active have been “welded” together with injected epoxies only to have the crack reoccur alongside the original crack.

(8) Is strengthening across the crack required? Is the crack structural in nature? Has a structural analysis been performed as a part of the repair program?

(9) What is the moisture environment of the crack?

(10) What will be the degree of restraint for the repair material?

b. Materials and methods to consider. Once these questions have been answered, potential repair materials and methods may be selected with the procedures shown in Figures 4-3 and 4-4. All of the materials and methods listed in these figures are described in Chapter 6. In most cases, more than one material or method will be applicable. Final selection of the repair material and method must take into account the considerations discussed in Sections 4-1 through 4-4 and other pertinent project-specific conditions.

4-8. Repair of Spalling and Disintegration

Spalling and disintegration are only symptoms of many types of concrete distress. There is no single repair method that will always apply. For example, placing an air-entrained concrete over the entire surface of concrete

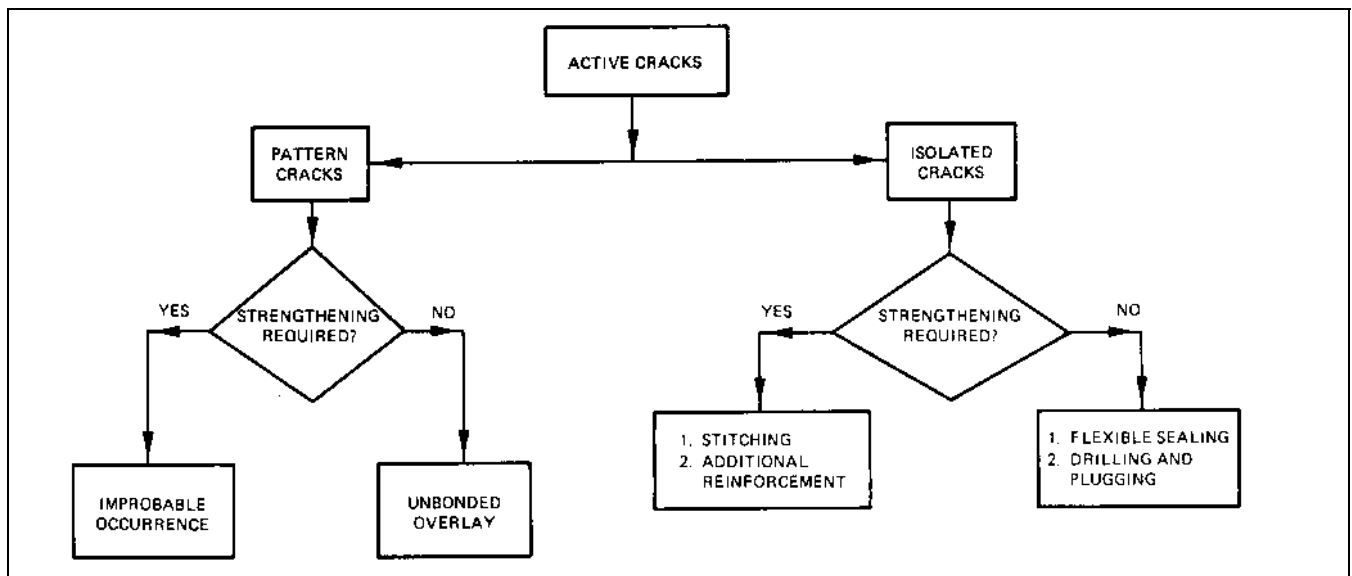


Figure 4-3. Selection of repair method for active cracks (after Johnson 1965)

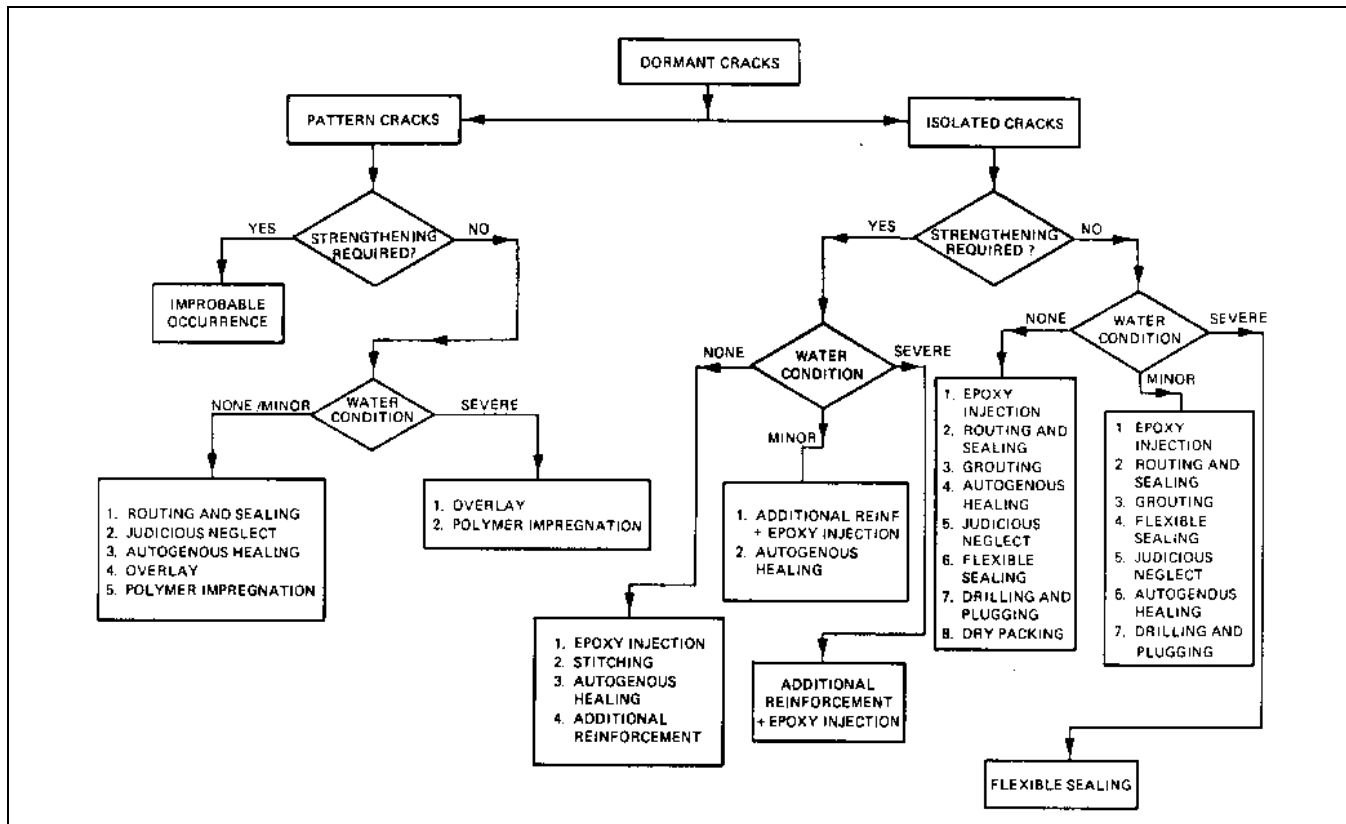


Figure 4-4. Selection of repair method for dormant cracks (after Johnson 1965)

that is deteriorating because of freezing and thawing may be a sound repair method. Use of the same technique on concrete deteriorating from strong acid attack may not be effective.

a. Considerations in selecting materials and methods. Selection of a method for repairing spalling or disintegration involves answering the following questions:

- (1) What is the nature of the damage?
- (2) What was the cause of the damage?

(3) Is the cause of the damage likely to remain active? If the answer to this question is yes, procedures for eliminating the factors contributing to the cause of damage should be considered. For example, if poor design details have contributed to freezing and thawing damage by allowing water to pond on a structure, drainage may be improved as part of the repair. Similarly, if attack by acid water has caused disintegration of a concrete surface, elimination of the source of the acid may eliminate acid attack as a cause of future problems. Knowledge of the future activity of a causative factor is

essential in the selection of a repair method. In the example just cited, elimination of the source of acidity might make possible a satisfactory repair with portland-cement-based material rather than a more expensive coating.

(4) What is the extent of the damage? Is the damage limited to isolated areas or is there major spalling or disintegration? The answer to this question will assist in the selection of a repair material or method that is economical and appropriate for the problem at hand.

b. General repair approach. Once these questions have been answered, a general repair approach can be selected from Table 4-1, which presents a comparison of the possible causes of spalling and disintegration symptoms and the general repair approaches that may be appropriate for each case. Table 4-2 relates the repair approaches shown in Table 4-1 to specific repair methods that are described in Chapter 6. As is true for repairing cracks, there will usually be several possible methods. The final selection must take into account the general considerations discussed in Sections 4-1 through 4-4 along with other pertinent project-specific considerations.

Table 4-1
Causes and Repair Approaches for Spalling and Disintegration

Cause	Deterioration Likely to Continue		Repair Approach
	Yes	No	
1. Erosion (abrasion, cavitation)	X		Partial replacement Surface coatings
2. Accidental loading (impact, earthquake)		X	Partial replacement
3. Chemical reactions			
Internal	X		No action Total replacement
External	X	X	Partial replacement Surface coatings
4. Construction errors (compaction, curing, finishing)	X		Partial replacement Surface coatings No action
5. Corrosion	X		Partial replacement
6. Design errors	X	X	Partial or total replacement based on future activity
7. Temperature changes (excessive expansion caused by elevated temperature and inadequate expansion joints)	X		Redesign to include adequate joints and partial replacement
8. Freezing and thawing	X		Partial replacement No action

NOTE: This table is intended to serve as a general guide only. It should be recognized that there are probably exceptions to all of the items listed.

Table 4-2
Repair Methods for Spalling and Disintegration

Repair Approach	Repair Method
1. No action	Judicious neglect
2. Partial replacement (replacement of only damaged concrete)	Conventional concrete placement Drypacking Jacketing Preplaced-aggregate concrete Polymer impregnation Overlay Shotcrete Underwater placement High-strength concrete
3. Surface coating	Coatings Overlays
4. Total replacement of structure	Remove and replace

NOTE: Individual repair methods are discussed in Chapter 6, except those for surface coatings which are discussed in Chapter 7.