PRELIMINARY REVIEW COPY

Technical Report Documentation Page

1. Report No. Preliminary Review Copy	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MATERIAL SELECTION GUIDELINE FOR STRUCTURAL CONCRETE REPAIRS		5. Report Date December 1998
		6. Performing Organization Code
7. Author(s) Brian Lee Lawrence, David W. Fowler, and Ramón L. Carrasquillo		8. Performing Organization Report No. 1412-S
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 0-1412
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Section/Construction Division P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Project Summary Report (9/97 — 8/98)
		14. Sponsoring Agency Code
15. Supplementary Notes Project conducted in cooperation with the Federal Highway Administration.		

16. Abstract

The Texas Department of Transportation is confronted with the monumental task of maintaining an extensive concrete infrastructure that is beginning to age and deteriorate. Maintenance of the transportation infrastructure is requiring more frequent and extensive levels of restoration. The process of restoring concrete structures can be both expensive and dangerous. The importance of performing quality repairs is underscored by these facts. To help better ensure the quality of the restoration efforts undertaken by the Texas Department of Transportation, a guideline with recommendations for the selection of concrete repair materials for use in structural concrete repairs was developed during the course of this research.

The guideline and recommendations provide the criteria for assessing the damage conditions and, from that, determining the performance requirements for both repair application techniques and proper material selection. Emphasis was placed on developing a guideline that, when combined with sound engineering judgment, can provide the basis for proper material selection.

17. Key Words Structure repair, concrete repair, material selection for structural concrete repair	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 90	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PRELIMINARY REVIEW COPY

MATERIAL SELECTION GUIDELINE FOR STRUCTURAL CONCRETE REPAIRS

by

Brian Lee Lawrence

David W. Fowler

and

Ramon L. Carrasquillo

Project Summary Report Number 1412-S

PRELIMINARY REVIEW COPY

Research Project 0-1412

Project title: "Repair of Structural Concrete"

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

December 1998

This report was prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

DISCLAIMERS

David W. Fowler, P.E. (Texas No. 27859)
Research Supervisor

ACKNOWLEDGMENTS

The authors acknowledge and appreciate the assistance provided by the TxDOT project director, Brian Lee Lawrence (MAT), as well as that provided by the other members of the project monitoring committee, which included B. Merrill (CMD), J. R. McDonald (ELP), and J. E. Rantz (LBB). In addition, we wish to acknowledge the assistance provided by Kathryn Holtz, Jeff Seiders, Joe Roche, Tomas Saenz, and Brian Merril, all of the Texas Department of Transportation Construction Division.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

1.1 PROBLEM STATEMENT

Along with our aging U.S. transportation infrastructure comes an ever-increasing need for repairs and restoration projects. In Texas, where a large part of the infrastructure is constructed of concrete, there are significant numbers of both on- and off-system bridges — constructed partially or completely out of concrete — that now require some level of restoration. Yet repairing or restoring concrete bridges is typically very expensive and, moreover, can be dangerous when the repair work is performed in proximity to traffic. For these reasons, performing successful and long-lasting repairs can be quite challenging. This becomes especially obvious when considering that the Texas Department of Transportation (TxDOT) now designs and constructs bridges that have an anticipated service life of 75 or more years. This means that many in-service bridges will have to function for periods much longer than were originally contemplated. As a result, making repairs and performing restoration will play an increasingly important role in extending the useful service life of such structures.

There are many factors encountered in each repair or restoration project that must be properly addressed to ensure a quality and long-lasting product. The most important and often most difficult factor is the selection of the repair material. Because of the many different types of repair materials, material selection can be a confusing and cumbersome process, one that is further complicated by a lack of nationally recognized standards or specifications. Other departments of transportation have in fact attempted to deal with this problem by establishing approved lists of repair materials for specific types of applications and environmental conditions unique to their state *(1)*. Frequently, however, the engineer is faced with having to make material selection recommendations based solely on the manufacturer's recommendations, rather than on a thorough understanding of the pertinent performance requirements.

Thus, a significant need exists for guidelines to aid the engineer in the material selection process. This need is especially critical in Texas, where environmental conditions vary dramatically within the state. There is a strong propensity to develop "cookbook" methods or approved materials lists to facilitate material selection, with such methods minimizing the need to fully understand the repair conditions and performance requirements. This approach has been avoided because most engineers understand that what works in one instance will not necessarily work in another, and that such methods can become obsolete or potentially stifling to innovation. This is a significant concern, given that the repair material industry is extremely dynamic, with new and innovative approaches to concrete repair always emerging.

In order for TxDOT to meet the challenges of not only maintaining but also extending the functional life of the transportation infrastructure, the tools for doing so must be developed. As in the case of concrete repair, a rational and systematic approach to selecting an appropriate repair material needs to be developed and utilized. This approach should address damage condition assessment, repair application techniques, and material selection. An approach such as this will help to improve the probability of performing successful repairs, while reducing or eliminating the trial-and-error process so commonly associated with concrete repair.

1.2 RESEARCH OBJECTIVES

The objective of the overall research project is to develop a guideline that can be used by the engineer for selecting an appropriate repair material. Recognizing that there can be a significant number of different types of commercially available repair materials that can potentially be used for a given application, this research focuses on identifying a suitable repair material *category,* rather than a specific *product.* It has been found that most of the commercially available products, and all of the repair materials historically used by TxDOT, can be grouped into five material categories distinguished by the material formulation *(1).* Such an approach ensures that the developed guidelines will not become obsolete too quickly, and that the final material selection will be based on engineering judgment.

Providing the engineer with the information necessary to make a final material selection requires that we develop a guideline that emphasizes consideration of all the influencing factors associated with a good repair. Accordingly, the guideline provides a strategy or "road map" that helps the engineer identify and appropriately weigh, for importance, these influencing factors. To identify the important factors of good concrete repair, the following four tasks were undertaken:

1. Identify the repair requirements unique to department-made repairs.
2. Identify the material categories.
3. Conduct the laboratory evaluation program.
4. Conduct the field evaluation program.

The findings of these tasks are addressed in the first two reports of the research project (1, 2) and summarized in Chapter 2 of this report. Two additional tasks, "synthesis of results" and "guideline preparation," serve as the basis for this third and final report.

1.3 SCOPE AND ORGANIZATION OF REPORT

This final report for Project 0-1412, "Repair of Structural Concrete," addresses the development and presentation of the concrete repair and material selection guideline. The guideline is based on the findings of the literature search and surveys, laboratory evaluation program, and field evaluation program. It is designed to serve two primary functions. The first function is to help the engineer make educated decisions regarding concrete repair; the second is to establish a consistent and systematic approach to repair material selection.

This report is divided into two main sections. The first section is a review and synthesis of the first two phases of this research project, which were addressed in reports 1412-1, "Material Selection Criteria for Structural Concrete" *(1)*, and 1412-2, "A Laboratory and Field Evaluation of Required Material Properties for Concrete Repair" *(2)*. The second section includes the strategies, developmental aspects, and final guideline for repair material category selection.

CHAPTER 2. BACKGROUND INFORMATION

2.1 INTRODUCTION

This chapter summarizes the findings reported in the first two documents, Reports 1412-1 and 1412-2, of this research project. Immediately following the summation is a discussion of how the findings of the first two phases of the research project support the development of the material category selection guideline.

2.2 RESEARCH REPORT 1412-1

Research Report 1412-1 reports the findings of a thorough investigation into the state of the art of structural concrete repair in North America. The objective of this investigation was to gain a better understanding of how material selection for concrete repair is being performed both in Texas and in the rest of North America. Through a literature review and through surveys of the Texas Department of Transportation (TxDOT) district offices and other transportation agencies in the United States and Canada, the most current philosophy on repair material selection was obtained. From this, a preliminary model for material selection was established. An overview of the four primary areas of Report 1412-1, shown below, are discussed in the following sections:

1. Types of Repair Materials
2. Repair Material Properties
3. Surveys
4. Selection Criteria

2.2.1 Types of Repair Materials

There are many different types of concrete repair materials, including commercially available and custom mix designs. In the 1994–1995 issue of *Aberdeen's Concrete Sourcebook (10),* over 120 manufacturers of concrete repair materials are listed, with each producing one or more types of material. This means that there are literally hundreds of different types of repair materials commercially available, not including custom mix designs.

Although the investigation revealed there are many different types of repair materials, most could be categorized into a small number of groups. The most distinguishing factor among different types of repair materials is the type of binder used. Repair materials generally are formulated with one of two different types of binders. The first is hydraulic cement, which is predominately composed of portland cement and magnesium phosphate-based binders. The second type of binder is polymer. The majority of polymer binders are either epoxy or acrylic. The other primary constituent found in repair materials is the filler. Fillers are normally used in all repair materials and serve a variety of purposes. The most common type of filler is natural aggregate.

Distinguishing between different types of repair materials by the type of binder provides an excellent means for establishing material categories, given that the type of binder primarily determines the properties of the repair material.

2.2.2 Repair Material Properties

Categorizing repair materials by the type of binder helps establish the framework by which the important mechanical, compatibility, and workability properties of repair materials can be distinguished. A significant amount of research has been performed to try to establish a better understanding of how the mechanical properties of repair materials with different kinds of binders vary. Research in this area has generally been directed towards trying to establish a correlation between the mechanical material properties, as measured in the laboratory, and actual in-situ performance. The mechanical material properties shown below are the characteristics considered essential to the satisfactory performance of a repair material. (Table 2.1 of Research Report 1412-1, included in Appendix B, identifies the typical physical properties of concrete repair materials.)

1. Bond
2. Plastic/drying shrinkage
3. Coefficient of thermal expansion
4. Modulus of elasticity
5. Permeability/absorption
6. Resistance to freeze thaw
7. Strength (compressive, flexural, tensile)

To date, there has been limited success in establishing a correlation between one or more of these characteristics to actual in-situ performance. The reason for this varies, but the most probable reason is owing to the difficulty of accurately modeling actual in-service conditions in the laboratory. There is, however, general agreement in the industry that bond strength, plastic shrinkage, and drying shrinkage are some of the more important individual mechanical characteristics.

The mechanical properties have historically been emphasized in previous research because these properties are measurable. Recently, more emphasis has been placed on the compatibility and workability of the repair material. The compatibility is a measure of the similarity between the repair material and the substrate *(4)*. The similarities are measured in terms of the differences in mechanical, chemical, and electrochemical properties between the two mediums. From this comes the philosophy that in order to ensure compatibility the repair material should be formulated similarly to that of the substrate.

The workability of a repair material is a measure of how well a material can be utilized in a given application technique and placement orientation *(6)*. The importance of good workability is rooted in the fact that it is a crucial ingredient for good workmanship. Previous studies, including the findings of the field evaluation program for this project, indicate that poor workmanship is consistently found to be a primary reason for premature failure of repair work. The problem is in defining and measuring the compatibility and workability requirements for a given repair. Without a sound understanding of the performance requirements necessitated by the repair conditions, including a thorough understanding of the repair material properties, it is difficult to make an appropriate choice of repair materials.

2.2.3 Surveys

The TxDOT district offices, fifteen states, and two Canadian provinces were surveyed to help identify the current practice of concrete repair in North America *(1)*. The survey contained four sections that addressed: 1) types of repair being performed, 2) types of repair procedures and contractual processes, 3) types of repair materials, and 4) repair material selection criteria. The other states and provinces were also asked to include their repair material specifications and approved repair material lists. The survey forms are included in Appendix A. Figures 3.3 and 3.4 of Research Report 1412-1, included in Appendix B, show the findings of the survey for the three most common types of damage and deterioration in TxDOT structures. The surveys of the TxDOT district offices revealed the information discussed below.

Most types of repairs fall into one of two categories. One is damaged concrete, primarily resulting from vehicle impact, while the other is deteriorated concrete, with corrosion-induced damage of bridge decks the leading cause of the deterioration. Correspondingly, bridges require the greatest amount of repair work of all structure types. Table 3.1 of Research Report 1412-1, included in Appendix B, shows the findings of the survey for average results of types of damage in Texas.

1. The districts appear to work very autonomously with respect to concrete repair. Most districts use one or two types of repair materials for all concrete repair work.
2. Relative to the amount of commercially available repair products, the districts reported using very few proprietary products. Once an acceptable material is found, the districts appear to continue to use that product in most applications.
3. The number of repair projects performed with plans and specifications is approximately equivalent to the number of repair projects performed by department maintenance forces. A significant amount of the repair work performed by district maintenance forces is performed without maintaining permanent records.

The survey of the states and provinces provided the following additional information:

1. Many of the agencies have formula/methodology-based specifications for repair materials and procedures. TxDOT falls into this category.

2. A common approach used by the states and provinces is the use of material approval testing programs. TxDOT does not have a formal material testing and approval program.
3. Some of the agencies have developed approved material lists. TxDOT does not maintain an official, approved list of repair materials.

The overall findings of the survey indicate that concrete repair and material selection is being dealt with in many different ways in Texas and in the rest of North America. Most agencies do not have a formal approach to assess and conduct concrete repair that is applied uniformly. A few of the states and provinces have developed extensive testing programs to identify acceptable materials for specific application orientation and for rapid-set materials. Approximately half of the survey responders have developed approved material lists. Most of the agencies that have repair material specifications use formula/methodology-based specifications.

2.2.4 Material Selection Criteria

The remaining portion of Research Report 1412-1 addresses material selection criteria and demonstrates the use of the selection criteria in two different case studies. The selection criteria are based on the findings of the literature search and surveys. By bringing this information together, a systematic approach has been developed. There are four primary steps identified in the material selection process. Each step, with a brief description, is identified below; Figure 4.1 of Research Report 1412-1, included in Appendix B, shows a "Material Selection Procedure" flowchart.

Step One: Evaluate and Define All Repair Conditions

The first step that must be taken in all repairs is to visit the repair site to perform a condition evaluation. The condition evaluation provides much of the information necessary for identifying the performance requirements of the repair material. A worksheet has been developed to aid in the condition evaluation process. This worksheet is divided into five categories:

1. Application conditions
2. Working time requirements
3. Strength gain requirements
4. Curing/finishing requirements
5. Long-term exposure conditions

Step Two: Define Application Method

The second step in the process is to identify the application method. Many types of materials are designed for a specific application method. Consequently, if the application method can be predetermined, the scope of materials can be narrowed. There are five general methods of application shown below. In the report, each method is described and a worksheet has been developed to aid in identifying the probable method.

1. Horizontal/poured
2. Hand applied
3. Formed and poured
4. Formed and pumped
5. Machine applied

Step Three: Select Potential Material Candidate(s)

The selection criteria for potential material candidates are based primarily on the application method and the performance capabilities of the repair material. This is determined either by the manufacturer's data or through independent testing.

Step Four: Develop a Material Specification

In this section, the process of building a specification is outlined. Fourteen possible components of the specification are examined and related to the initial condition assessment. Each component addresses a specific material property or repair procedure. Industry standards of practice, including test methods and permissible test result values, are identified. The user simply selects the appropriate components and builds the framework for the material specification. The fourteen components are shown below:

1. Shrinkage
2. Chemical composition
3. Bond strength
4. Absorption
5. Freeze/thaw resistance
6. Consistency
7. Setting time
8. Strength and rate of strength gain
9. Flexural strength
10. Coefficient of thermal expansion
11. Curing
12. Texture
13. Color
14. Abrasion

Two case studies, including the repair of an impacted prestressed concrete beam and void repair in a U-shaped prestressed concrete beam, are used as example applications of the material selection criteria. In each case, the step-by-step process is shown and discussed in detail.

2.3 RESEARCH REPORT 1412-2

Research Report 1412-2 addresses the findings of the laboratory evaluation program of concrete repair materials and the field evaluation program of in-service concrete repairs *(2)*. The objective of the evaluation programs was to identify data for use in the development of the material selection guidelines. The mechanical, durability, and compatibility properties of nine different types of repair materials were tested in the laboratory evaluation program to try to identify the important performance characteristics, as well as the characteristics that are not as important and that could therefore be disregarded. An emphasis was placed on testing for dimensional stability.

Testing of in-service repairs was conducted around Texas to determine if there were other factors involved in performing successful concrete repairs, and to identify possible areas of correlation to the laboratory evaluation results. However, the primary intent was to gain a better understanding of the quality of repair work in Texas and to learn about possible influencing factors not addressed by the laboratory program. The information from both programs will provide the basis for developing the final material-category selection guideline. An overview of the four primary areas of the report shown below are discussed in the following sections:

1. Performance criteria
2. Material selection
3. Laboratory evaluation program
4. Field evaluation program

2.3.1 Performance Criteria

For Research Report 1412-1, we developed a preliminary process for selecting a repair material by determining current industry standards of practice in North America and by synthesizing the information into selection procedures. From this the primary step for developing performance criteria was identified as conducting a condition evaluation of the repair site. From the findings of the condition evaluation, basic performance requirements for the repair material can then be identified. By knowing the performance requirements and other pertinent factors, such as the type of application process, one can then identify an appropriate material category.

The greatest difficulty with this approach is that attempts to correlate the measured mechanical material properties to in-situ performance have not been fully successful. Even if this were possible, there is no unique set of parameters for the mechanical material properties of repair materials that are applicable to all materials and repair conditions. Understanding the performance requirements dictated by the repair site conditions and the preferred application method is the first important step in isolating an appropriate repair material category. However, without knowing the performance requirements dictated by the damage condition and the actual performance capabilities of the selected material category, the engineer will still be left with too many variables.

For example, when performing vertical or overhead repair work, it is intuitively obvious that bond strength is critically important. The question is, What level of bond strength is required for ensuring that the type of repair material selected will stay bonded to that particular repair condition? Generally, the material with the highest reported bond strength will be selected, and this may actually prove to be acceptable in many situations. However, making such a decision without regard to other factors, such as compatibility, can lead to serious problems.

For example, while epoxy-based materials typically have very high bond strength characteristics, they are also among the most incompatible of materials, a characteristic that can lead to premature failure. Under these circumstances, it may be prudent to use a material that perhaps lacks the excellent bonding properties of the epoxy-based materials but that has better compatibility characteristics.

To deal with this problem, there have been several recent studies that have attempted to correlate laboratory-measured material properties to actual in-service conditions. All of these efforts have met with limited success. A promising new study — "Performance Criteria of Concrete Repair Materials, Phase One" *(5)* — being conducted by the United States Army Corp of Engineers is actually focusing on compatibility characteristics. Because the project has just gotten underway, there have not yet been any reported findings.

The present research project was conducted to help eliminate some of the variables that the engineer faces in the material selection process. Emphasis was placed on developing a correlation of compatibility to the mechanical material properties. From this, and with respect to the Texas environmental conditions, the compatibility performance parameters necessary for developing the guideline were established.

2.3.2 Material Selection

The selection of the material categories, along with the actual materials to use in the laboratory program, was based on the findings of the surveys conducted in the first phase of this research project. Five material categories were selected to better represent the different types of materials used in Texas. Distinguishing the categories are the types of binder, which are shown below.

1. Portland cement concrete (PCC)
2. Magnesium phosphate concrete (MPC)
3. Epoxy polymer concrete (epoxy PC)

4. Methyl methacrylate polymer concrete (MMA PC)
5. Latex-modified concrete (LMC)

Different types of repair materials from each category were selected for evaluation. The materials selected are those that are typically used by TxDOT for concrete repair or that represent above-average quality for the corresponding material category. Table 3.6 of Research Report 1412-2, included in Appendix C, shows the " Reported Material Property Values of the Proprietary Products." Nine different types of materials, shown below in Table 2.1, were chosen.

Table 2.1 Repair materials and sources

Category	Product Type/Name	Manufacturer
I (PCC)	Duracal TxDOT Class "K" Emaco S88-CA	U.S. Gypsum N/A Master Builders
II (MPC)	Set 45 Hot Weather	Master Builders
III (Epoxy PC)	TxDOT Type VIII Burke Epoxy Mortar	Industrial Coatings Burke
IV (MMA PC)	T 17 Polymer Concrete	Transpo
V (LMC)	Sika Top 122 Burke-Krete Overlay Repair Mortar and SBR	Sika Burke

When possible, the materials were tested both in neat conditions (without the addition of aggregates) and in fully extended conditions, with aggregates based on manufacturer's recommendations. The materials were generally tested in a consistency typical of the consistency in which they are normally used.

2.3.3 Laboratory Evaluation Program

The laboratory evaluation program was designed to evaluate the basic material properties identified as the most relevant properties for ensuring successful concrete repair in the Texas environment. The overall environmental conditions in Texas are generally not considered to be harsh. There are some notable exceptions, such as areas with high sulfates in the soils and groundwater. The districts also use chemical deicing agents, many of which can be deleterious to the concrete. For the in-service structures that are nearing the original design life expectancy, many have been exposed to significant levels of chloride-based deicing agents. Additionally, some regions in Texas are subject to frequent broad-range thermal cycles. To appropriately address environmental thermal cycling, emphasis was placed on testing the dimensional stability characteristics of the repair materials. Three categories of material properties were evaluated:

1. Mechanical
2. Compatibility
3. Durability

Selected properties were measured for each category. The specific tests are shown below in Table 2.2. Table 5.7 of Research Report 1412-2, included in Appendix C, shows a "Comparison of Material Properties by Ranking."

Table 2.2 Material properties and testing measures

Mechanical	**Test Method**
Compressive Strength	ASTM C39
Flexural Strength	ASTM C78 & C348
Compatibility	**Test Method**
Modulus of Elasticity	ASTM C469
Shrinkage	Dupont
Coefficient of Thermal Expansion	ASTM C531
Bond	ACI-503R Modified
Durability	**Test Method**
Absorption	ASTM C413
Abrasion	ASTM C418
Permeability	ASTM C1202

A significant aspect of the laboratory evaluation program was the bond strength testing. There are various ways to measure bond strength. An adaptation of ACI-503R, Direct Pull-Off Test *(7),* was used in this project. A primary reason for using this method was to assess the method for use in field applications. The testing was performed on TxDOT Class "S" concrete *(11)* samples measuring 300 mm x 300 mm x 89 mm, with the repair material applied in an overlay fashion to the samples. For most of the different types of repair materials, the material was applied to the concrete samples in three different thicknesses. After curing, initial bond strength measurements were obtained.

The samples were placed in an environmental chamber after the initial bond testing and allowed to thermally cycle four times a day for one week at temperatures ranging first between 10°C to 35°C, and then between -12.2°C to 15.5°C for the next week. The thermal cycling simulation continued for a specific number of cycles between each series of pull-off testing.

The purpose of performing this type of test was to determine what effect dimensional stability of the repair material with respect to the substrate has on the performance of the repair material in terms of bond strength. This is based on the understanding that stresses located along the bond interface, if sufficiently high, can result in degradation of bond strength with time. Therefore, if a significant reduction of bond strength is not noted with respect to time, then in theory the material can be considered physically compatible with the concrete.

The mechanical properties of the nine materials tested had compressive and flexural strengths equal or superior to typical class "S" concrete strengths. The compatibility properties identified were modulus of elasticity, shrinkage, and coefficient of thermal expansion. The compatibility properties were found to be comparable for material categories PCC, MPC, and LMC. The results for the polymer-based materials were found to be two to four times higher than those of ordinary concrete. Of special interest are the shrinkage results of the MMA-PC material and the coefficient of thermal expansion for the extended epoxies. The MMA-PC material experienced the highest amount of shrinkage. Extending with aggregates reduced the coefficient of thermal expansion of the epoxy polymer-based materials.

The results of bond strength testing generally supported the findings of the compatibility testing. Table 5.2 of Research Report 1412-2, included in Appendix C, shows the "Results of Bond Strength Test." The materials found to have large variations in the compatibility properties appeared to be more prone to premature failure. This is supported by the fact that the only materials to completely fail and lose all bond strength were the neat epoxies. However, it should be noted that most of the materials performed with very little loss of bond strength, an indication that under the conditions of the laboratory testing program the materials were found to be compatible when applied to undamaged, good quality class "S" concrete specimens.

2.3.4 Field Evaluation Program

The field evaluation program of in-service repairs was conducted to identify possible correlation with the laboratory evaluation program and to assess the overall quality of repair work performed in Texas. From this, other known factors that influence the quality and performance of in-service repairs were investigated. The program involved four different activities:

1. Site selection
2. Field testing
3. Laboratory testing
4. Synthesis of results

The geographical sites were selected to represent the diverse Texas environmental conditions. Nine sites were selected that provided diversity in terms of environmental conditions, types of repair materials, repair orientation, and age of repair. Figure 6.1 of Research Report 1412-2, included in Appendix C, shows the "Locations Investigated during the Field Evaluation Program." Nineteen different types of repairs were evaluated both qualitatively and quantitatively. The qualitative evaluation consisted of gathering the background information, including material and repair information, site conditions, workmanship, and overall general performance. The quantitative evaluation consisted of bond strength testing using the same test that was used in the laboratory program (ACI-503R).

The bond strength testing revealed those repairs older than 1 year typically had bond strengths of approximately 0.9 MPa, while repairs younger than this had strengths ranging from 50 to 300 percent higher. The primary cause of failure appeared to be poor workmanship or environmental conditions that exacerbated the compatibility difference between the repair material and unsound substrate. In most situations, the delaminated repair material appeared to be in good condition.

Samples of the repair material from the field were obtained when possible and tested in the laboratory for coefficient of thermal expansion. The findings of the testing revealed that the epoxy materials generally had substantially higher coefficients than the cementitious materials.

A significant amount of information was obtained during the field evaluation program. The amount of field testing limited the possibility of developing any sound correlation to the laboratory evaluation program due to the relatively small sample size. However, the overall findings of the quantitative testing revealed that the in-service bond strengths were generally found to be one-half to one-third of the values observed in the laboratory, with most of the failures occurring at the interface between the repair material and concrete substrate. The difference appears to be primarily related to substrate conditions, workmanship, and environmental conditions. Table 6.19 of Research Report 1412-2, included in Appendix C, shows a "Comparison of Field Evaluation Sites."

The use of ACI 503R for bond testing exhibited real promise in providing a technique for in-service measurement of material performance that can be used for job control testing and long-term monitoring. The test is, however, influenced by many different variables, which reduces its accuracy and repeatability. These factors have to be accounted for appropriately.

CHAPTER 3. SYNTHESIS OF PREVIOUS RESEARCH

3.1 OVERVIEW

The first two phases of this research project, addressed in Research Reports 1412-1 and 1412-2, presented the findings of the literature search, the laboratory evaluation program, and the field evaluation program. The literature search was conducted to determine the current state of the art in concrete repair procedures and repair material selection throughout North America. The laboratory evaluation program was conducted to assess the typical material properties of the repair materials presently used in Texas; it also sought to identify the important material properties as they pertain to repair material performance with special emphasis on compatibility. The field evaluation program was performed to assess qualitative and quantitative characteristics of in-service concrete repairs throughout Texas.

The goal of the first two phases of this research was to build a knowledge base for use in the development of concrete repair and material selection guidelines to be used by TxDOT engineers. Recognizing that there are many variables that can influence the performance characteristics of concrete repairs — variables that have proven to be difficult to measure and correlate to actual in-service performance — the first two phases of the research were designed to build on the current level of theoretical and empirical technology. Using this approach, and by focusing specifically on concrete repair in the Texas environment, we effectively reduced the scope of the research and the corresponding number of variables. The following synthesis of the first two phases of this research identifies the key supporting elements used for developing the guidelines.

3.2 SIGNIFICANT FINDINGS, ASSUMPTIONS, AND DEFINITIONS

Our primary purpose in developing the material category selection guideline is to provide engineers with a systematic approach for identifying the important performance characteristics necessitated by given damage conditions. Using this information, engineers will then be able to determine the most appropriate repair material. The techniques of concrete repair have long been established; and while this research project and previous research projects indicate that a lack of attention to good concrete repair practice is probably the leading cause of premature failure, the emphasis of the guideline remains with the material selection process. Many U.S. states and Canadian provinces have developed various techniques for aiding the engineer in this process. The most common approach is the use of approved materials lists in combination with methodology-based specifications. To develop a guideline that will allow for innovation and engineering judgment to be used in the selection of an appropriate material category, the guideline was developed without dependency on or encouragement for approved materials lists.

The synthesis of this research is divided into two sections. The first section is *Repair Material Technology,* which addresses the type and categorization of materials. This section also identifies the important aspects of the material properties in relation to performance criteria. The second section is *Material Selection Criteria,* which outlines the approach and rationale used for developing the repair material category selection guideline.

3.3 REPAIR MATERIAL TECHNOLOGY

There are hundreds of different types of commercially available repair materials *(10).* The engineer may also choose to develop a custom design repair material, which even further increases the number of possible choices. The process of selecting the most appropriate repair material starts with understanding that for any given repair there is probably more than one type of material that can be used successfully. Having a strong understanding of the differences between the different types of materials helps the engineer to narrow the field of possible choices.

3.3.1 Material Types

There are many important factors to be considered when selecting a repair material. One factor that has not been previously addressed in the first two phases of the research is the quality and consistency of the repair material. The use of quality repair materials capable of providing a consistent formulation should be a fundamental requirement. One way to help ensure this requirement is met is to use proprietary materials provided by reputable manufacturers. There are certain exceptions to this recommendation, such as situations where very large volumes of material are required and, as a consequence, the economics mandate the use of normal concrete. However, in most situations the benefits of using commercially available proprietary materials far outweigh the disadvantages.

There are two important reasons for this recommendation. The first is that a reputable manufacturer typically will be able to provide the important material property data required by the engineer for the selection process. A reputable manufacturer will generally be willing to provide performance history and guarantees. The second reason is that most reputable manufacturers will have a quality control program to ensure the quality and consistency of the repair material. Custom mix designs that require proportioning on the job site may be more suspect to variation in quality and consistency. Custom mix designs also require testing to establish the performance characteristics that the engineer will need to properly evaluate the material.

3.3.2 Material Classification

Most repair materials are formulated for specific application conditions. The performance characteristics are predominately controlled by the type of binder. For this reason, categorizing based on the type of binder is a logical approach. The five categories of repair materials, identified in Research Report 1412-2 and shown below, are differentiated by the type of binder. The five categories represent the majority of the different types of repair materials commercially available and the different types of materials presently used by

TxDOT. Although Category 1 was identified as portland cement concrete in Research Report 1412-2, it will be classified as hydraulic cement concrete (HCC) in the remaining portion of this report and in the guideline to appropriately address other nonportland cement-based hydraulic cementitious materials used in many concrete repair materials.

1. Hydraulic cement concrete (HCC)
2. Magnesium phosphate concrete (MPC)
3. Epoxy polymer concrete (Epoxy PC)
4. Methyl methacrylate polymer concrete (MMA PC)
5. Latex-modified concrete (LMC)

Research Report 1412-2 provides the findings of the laboratory evaluation program. Each category of material was evaluated to determine the individual physical properties of typical repair products selected from the different categories. The individual material properties are classified into three areas of material characteristics: compatibility, durability, and mechanical.

Compatibility is a measure of the similarity of properties of the repair material and the substrate that affect bond *(1, 4)*. A balance between the physical, chemical, and electrochemical properties of the two mediums must be obtained to achieve compatibility. When using proprietary products specifically formulated for concrete repair, chemical and electrochemical incompatibility generally is not a concern. The most frequent concern regarding chemical compatibility occurs in repairs where the reinforcing steel is corroding. In this situation special attention should be given to the selection of a material that will not exacerbate the corrosion process. The physical compatibility is controlled by four primary properties: modulus of elasticity, shrinkage, creep, and coefficient of thermal expansion. One or all of these properties can lead to premature bond failure of a repair if a balance is not achieved between the repair material and substrate.

Durability is defined as the resistance to deterioration caused by chemical attack, harsh environmental conditions, or abrasion *(4)*. The durability of the repair products was measured in the second phase of this research project. Absorption, abrasion, and permeability were the three material properties measured for determining the relative level of durability.

Mechanical properties of the repair materials are the properties that are measured in terms of strength *(3)*. In phase two of this research project, compressive and flexural strengths were the measured mechanical properties. The bond strength measurements were included as a measure of compatibility. The reason for doing this was to try to correlate the loss of bond strength with respect to time and exposure to thermal cycles. This theoretically provides a measure of compatibility. A meaningful statistical correlation was established only for the neat epoxy materials, which eventually lost all bond strength during thermal cycling.

The material properties classified by the compatibility, durability, and mechanical characteristics only represent part of the important material properties for concrete repair. Other important properties, such as material consistency, set time, aesthetics, and cost, frequently are factors in the selection process. These material properties directly impact the contractor or user and are accordingly classified as *User Requirements* or treated independently. A review of the five material categories and related material properties is provided below.

Category I — Hydraulic Cement Concrete (HCC)

This category represents the largest number of different types of repair materials. The most commonly used binder for repair materials in this category is portland cement. In recent years, however, a number of other hydraulic cement binders have become popular for use as the primary binder or partial substitutes and additives for portland cement. Materials such as fly-ash, microsilica fume, and ground granulated blast furnace slag are a few examples. These repair materials are often combined with various admixtures, specialized fillers, and fibers to improve performance characteristics.

1. User Requirements:
   a) Generally the most economical repair material
   b) Can be used for most orientations and ranges of thickness
   c) Can be applied by all application methods
   d) Can be formulated to provide for rapid set characteristics
   e) Can be formulated to meet aesthetic requirements
2. Compatibility: HCC materials are the most compatible materials because of their similarities to the materials of the concrete substrate. One notable concern is shrinkage. Low-shrinkage materials are available and should be used unless it is known that shrinkage will not affect the performance of the repair.
3. Durability: When using proprietary materials, durability will rarely be a concern. Most proprietary materials are formulated to provide durability characteristics as good as and generally substantially better than those of normal concrete.
4. Mechanical: HCC materials can be formulated to provide a wide range of compressive and flexural strength values. While some of the HCC proprietary materials can develop excellent bond strength, generally these materials are going to provide only moderate to good bond strengths. However, because of the excellent compatibility properties, the bond strength requirements may not be as critical.

Category II — Magnesium Phosphate Concrete (MPC)

This category of repair material can also be classified as HCC. The main difference with MPC and the other hydraulic cementitious materials is that the binder is magnesium phosphate based as opposed to portland cement, which is primarily composed of calcium-silicate hydrates *(6)*. This material also provides significant differences in material characteristics that further set it apart from other HCC products. For example, MPC is a very rapid setting material that bonds exceptionally well to a dry substrate. This material is very sensitive to variations in the amount of required mixing water and can develop a high exotherm during hydration *(3)*.

1. User Requirements:
   a) Can be used for most orientations and ranges of thickness
   b) Can be applied by most application methods
   c) Is a rapid-setting and rapid-strength-gaining material
2. Compatibility: The compatibility characteristics of this material are very similar to those of the HCC materials. MPC materials generate high temperatures during hydration. Thermal effects caused by the exotherm should be considered when using this material.
3. Durability: MPC materials have durability properties similar to those of HCC materials, with the notable exception of high permeability.
4. Mechanical: MPC materials develop high flexural and compressive strengths. The bond strength is similar to that of the HCC materials.

Category III — Epoxy Polymer Concrete (Epoxy PC)

This category represents a wide variety of different types of repair materials. Epoxy, which serves as the binder, is part of the polymer family. There are many different types of epoxies that can be extended with a variety of aggregates and fillers. The characteristics of the EPC repair material can be greatly influenced by using different types of epoxies or by the type and amount of aggregates or fillers that are used to extend the epoxy. Properties such as the modulus of elasticity, coefficient of thermal expansion, set time, and strength are some of the characteristics that can be modified.

1. User Requirements:
   a) Expensive
   b) Can be formulated for most orientations
   c) Very limited thickness ranges
   d) Hand application by trowel
   e) Provides for rapid set characteristics
   f) Difficult cleanup
   g) Chemical hazards
2. Compatibility: Epoxy PC materials are some of the least compatible materials because of the inherently high coefficient of thermal expansion associated with epoxies. The coefficient of thermal expansion can be lowered by extending the

epoxy with aggregates or other types of fillers, but a good match to that of the substrate generally cannot be obtained. These materials also generate very high temperatures during the curing process *(3)*. Thermal effects caused by the exotherm should be considered when using this type of material.

3. Durability: Epoxy PC materials have excellent durability properties.
4. Mechanical: Epoxy PC materials can be formulated to provide a wide range of compressive and flexural strength values. High early strengths are a common characteristic of all epoxies. These materials also provide excellent bond strength characteristics.

Category IV — Methyl Methacrylate Polymer Concrete (MMA-PC)

This category of repair material represents a type of acrylic-based polymer that is specifically formulated for various types of concrete repair. Acrylics can be used for concrete crack sealing, for thin overlays, and for damage repair. There are a limited number of suppliers that actually formulate and package the material as a concrete repair material. It has often been used for the above applications by purchasing the MMA binder separately and extending the binder with aggregate as deemed necessary. High molecular weight methacrylate (HMWM) is a more recent development that offers the added benefits of less odor and longer working times.

1. User Requirements:
   a) Expensive
   b) Formulated for horizontal or formed orientations
   c) Very limited thickness ranges
   d) Provides for rapid set characteristics
   e) Difficult cleanup
   f) Chemical hazards, strong odor, and flammable until cured
2. Compatibility: MMA-PC materials are very similar to Epoxy PC materials with the added disadvantage of moderate shrinkage.
3. Durability: MMA-PC materials have excellent durability properties.
4. Mechanical: The compressive and flexural strengths of the MMA-PC materials are similar to or higher than those of the EPC materials. These materials also provide excellent bond strength characteristics.

Category V — Latex-Modified Concrete (LMC)

This category of repair materials actually can be classified as HCC. Latex-modified concrete is cementitious-based material with a latex additive. It is treated as a separate category because most material manufacturers also treat LMCs separately. The repair materials represented by this category are referred to by such various names as acrylic latex-or polymer-modified cementitious concrete. Some latex additives are available in a powder form that is often premixed with the other repair constituents and provided in bags. It is also provided in a liquid state. Ordinarily, the latex is mixed with the appropriate amount of water and provided as a two-part system: one part water with the latex and the other part consisting of the dry constituents supplied in a bag.

1. User Requirements:
   a) Can be used for most orientations and ranges of thickness
   b) Can be applied by all application methods
   c) Can be formulated to provide for rapid set characteristics
   d) Can be formulated to meet aesthetic requirements
   e) Has a very short finishing time owing to formation of surface skin
2. Compatibility: LMC materials are similar to PCC materials but have improved shrinkage characteristics.
3. Durability: LMC materials have very good durability properties. The latex additive makes this material substantially more watertight (e.g., low absorption and permeability) than normal concrete.
4. Mechanical: LMC materials can be formulated to provide a wide range of compressive and flexural strength values. Generally, the LMC materials develop excellent bond strength and have a modulus of elasticity lower than that of normal concrete.

3.4 CRITERIA FOR THE MATERIAL CATEGORY SELECTION GUIDELINE

The following conditions (identified in the research project statement) and several basic assumptions were taken into consideration to help narrow the focus of the guideline:

3.4.1 Rationale

1. The intent of the research is to develop a user-friendly guideline, not to develop an approved list of repair materials.
2. The guideline should provide the necessary rationale for directing the engineer to an appropriate material category while allowing engineering judgment to be used for the actual repair material selection.
3. The guideline should be flexible enough to accommodate innovation in the repair material industry.
4. Based on the findings of the district survey, and in accordance with the intent of the research project, the guideline should focus on repairs of structural concrete excluding pavement repair. Specific consideration should be given to the fact that bridge repairs represent the majority of structural concrete repairs performed by the districts.
5. Repairs conducted in or near traffic should be considered as high-risk types of

repairs. In such situations, cost of the repair material should not necessarily be a primary factor in the material selection process.

6. Commercially available proprietary repair materials should be used when possible. Custom mix designs generally will not offer any advantage over a properly selected proprietary repair material — with the possible exception of cost. The most common exceptions are repairs that require large volumes of material. However, in not using proprietary materials, many valuable benefits are lost, including material technical data sheets; directions for proper mixing, application, and curing; performance guarantees or warranties; technical support; and often repair specifications that can be obtained through the repair material supplier. Additionally, the material properties will likely not be known for custom mix designs. When used, custom mix designs should be tested to determine the material properties necessary for making an informed selection. Additionally, a comprehensive specification should be developed to address the pertinent elements required for effecting a good repair.

3.4.2 Format of Guideline

The remaining portion of this report follows a systematic approach for concrete repair. Chapter 4, "Condition Assessment," provides guidance for performing a comprehensive condition assessment that includes methods for identifying and determining the extent of damage. Chapter 5, "Repair Performance Requirements," identifies and provides a comprehensive discussion of the pertinent performance requirements. Chapter 6, "Repair Material Application Techniques," describes the most common methods for applying repair materials. Chapter 7, "Selection of a Repair Material Category," presents the selection instruments. The final chapter, Chapter 8, reports the conclusions of the study.

CHAPTER 4. CONDITION ASSESSMENT

4.1 BACKGROUND

The first and often most important step in the repair process is conducting a condition assessment. The field evaluation program addressed in Research Report 1412-2 identified many potential causes of unsuccessful concrete repair. There are clearly many variables that, if not considered and appropriately addressed, may lead to premature failure of repair work. For the engineer responsible for designing and overseeing a repair project, performing a proper and thorough condition assessment will increase the probability of a successful project more than any other single phase in the process. The three primary tasks to be considered as part of the condition assessment process are shown below and addressed in further detail as follows:

1. Documentation of existing conditions
2. Damage assessment
3. Identification of the repair performance requirements

4.2 DOCUMENTATION

Documentation of the existing damage conditions is necessary. This information will be referenced throughout the repair procedure development process and will serve as a basis of comparison for performance evaluation of the finished repair work. When possible, this should include drawings and photographs of the damaged areas. A permanent file should be established for maintaining this information as well as other such information as condition assessment, contractual, and as-built documentation.

The lack of documentation for repair projects in the department was evidenced by the district survey. In discussions with district personnel, we received many comments regarding the loss of expertise that occurs when key department employees retire. These employees had developed a long history of repair experience, with much of this experience gained by a trial-and-error approach to concrete repair. Documenting on a project basis the knowledge gained through many years of concrete repair could ensure that such information is maintained and, most importantly, shared.

4.3 DAMAGE ASSESSMENT

Performing a comprehensive damage assessment provides the basis for successful repair work. The damage assessment is conducted to determine the cause of the damage, identify the condition or "soundness" of the substrate concrete, measure the extent of damage, and ascertain the structural significance of the damage. This aspect of the repair process is often underemphasized. For large projects, this can be the most time-consuming portion of the project development for the engineer. Figure 4.1 illustrates the steps undertaken in conducting a damage assessment. Each aspect of the process is addressed in further detail below.

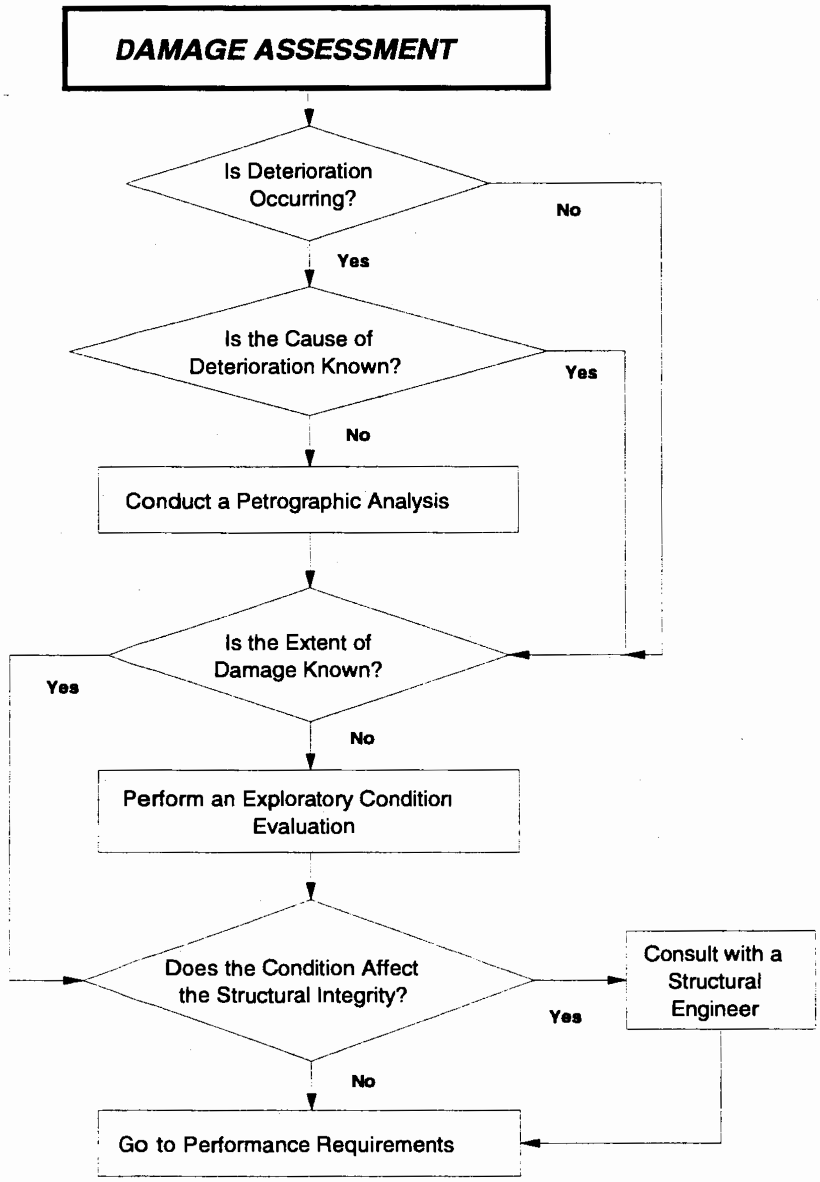


Figure 4.1 Damage assessment flowchart

4.3.1 Cause of Damage

The cause of the damage is often already known or visibly evident; however, this is not always the case. As demonstrated by the results of the district surveys, documented in Research Report 1412-1, approximately 50 percent of all repair work is attributed to damage caused by vehicular impact. The remaining 50 percent is attributed to deteriorated or defective concrete. In such situations, it is important to accurately identify what caused or is causing the deterioration, to help ensure proper identification of the required mitigating measures and to aid in the repair material selection process.

A typical approach in performing a concrete forensics investigation is to core the structure in both the damaged and undamaged areas for evaluation and comparative purposes. Such techniques as petrography, chemical analysis, and strength testing can be used to help identify the cause and extent of the concrete damage.

Petrographic analysis, conducted in accordance with ASTM-C856, "Practice for Petrographic Examination of Hardened Concrete," involves a detailed study of the concrete matrix and of the individual concrete constituents. By optical microscopy and other analytical procedures — such as scanning electron microscopy, distress mechanisms caused by chemical attack, and environmental conditions — defective materials and poor construction practices can often be identified. Chemical analysis can also aid in determining the presence and quantity of certain elements, minerals, and compounds. Physical and nondestructive strength testing can help to quantify and isolate the extent of the damaged regions.

4.3.2 Exploratory Condition Evaluation

Determining the overall extent of the damage is essential for estimating the quantity of required repair work and for assessing the structural effects of the damage. The importance of this aspect of the damage assessment process is often underestimated. Without a clear understanding of the extent of the damage, the repair project will be much more susceptible to cost overruns and delays. A lack of understanding of the damage also increases the level of difficulty for inspecting the repair construction.

There are a variety of destructive and nondestructive testing procedures that can be used to assess the extent or magnitude of the damage. As noted above, petrographic evaluation and strength testing are two such tools, both of which are available within the department. Additionally, there are many nondestructive testing techniques utilizing both old and new technologies that can be successfully used for precisely quantifying and isolating the extent of the damaged regions. Many of these tools are also available within the department. A good reference source for nondestructive testing techniques is ACI 228.1R, "In-Place Methods to Estimate Concrete Strength, Part 2."

The relative condition of the substrate concrete is commonly referred to as the "soundness" of the concrete. As discovered in the field evaluation program, many of the in-service repairs evaluated were found to have premature bond failures because the repair materials were applied to unsound concrete. Prior to repair, all damaged concrete should be removed to a level where the substrate concrete is sufficiently sound. Based on the findings of this research, the recommended minimum tensile strength of the substrate concrete and the bond of the repair material to the concrete, measured in accordance with ACI-503R, "Direct Pull-Off Test," should be approximately 1.5 MPa or greater *(2)*. If the condition of the substrate does not meet this recommended level of soundness, additional concrete should be removed until sound concrete is revealed.

When concrete repair work must be performed on unsound concrete, the importance of ensuring compatibility between the repair material and the substrate becomes paramount. This point was demonstrated in the laboratory testing program, where compatibility was not found to be a significant factor in the performance of the repair materials applied to the newly cast concrete specimens. The only notable exception was the neat-epoxy repair materials that have extremely high coefficients of thermal expansion (C of E) properties. Conversely, many of the in-service repairs made to unsound concrete were found to be performing very poorly.

4.3.3 Structural Significance

The final step of the damage assessment process is to determine the structural significance of the damage. The majority of concrete repairs performed by the department are not considered to be structural repairs. Structural repairs are repairs that are performed to reestablish lost structural capacity. Generally, most repair work is performed to reestablish concrete cover for protection of the reinforcement and for aesthetics. When a structural analysis indicates that a critical loss of structural capacity has occurred as a result of the concrete damage, the structural engineer should first determine the feasibility of strengthening the structure before proceeding any further in the material selection process.

4.4 REPAIR PERFORMANCE REQUIREMENTS

The performance requirements for the repair material, such as orientation, depth, strength, and other factors that are needed for proper material selection, are addressed in Chapter 5. The performance requirements are noted herein to emphasize the fact that much of the information associated with establishing these factors was obtained during the condition assessment process.

CHAPTER 5. REPAIR PERFORMANCE REQUIREMENTS

5.1 BACKGROUND

The last task identified in Chapter 4 is the identification of the repair performance requirements. All the information — with the exception of determining the structural adequacy of a damaged structure — can generally be obtained during the condition assessment process. In performing the condition assessment, the information obtained for the repair performance requirements needs to be properly documented. In Research Report 1412-1, a preliminary worksheet titled "Condition Evaluation" was developed for this purpose *(1)*. This worksheet provides the engineer with a checklist approach to identifying pertinent repair performance requirements.

In this final version of the guideline, a similar approach is taken with some modifications. A worksheet for identifying the repair performance requirements has also been developed for simplifying the data-gathering process. This worksheet is shown in Figure 5.1. While similar in format and content to the worksheet developed in Research Report 1412-1, changes have been made to tailor the worksheet to the needs of the department and for consistency purposes. This worksheet contains the six categories: 1) Repair Geometry, 2) Substrate Conditions, 3) Structural Significance, 4) Work Accessibility, 5) Environmental Conditions, and 6) Repair Aesthetics.

5.2 PERFORMANCE CATEGORIES

A description of each category contained in the worksheet is provided below. The description includes a discussion of associated performance requirements.

5.2.1 Repair Geometry

The repair geometry refers to the orientation and physical dimensions of the damaged region in the structure. Orientation of the repair is generally characterized as being in a *horizontal, vertical,* or *overhead* position. The orientation for which a repair material is formulated is identified in the manufacturer's specification datasheet. Many repair materials are actually formulated for specific orientations, such as overhead materials that may be formulated with lightweight fillers to allow for greater depth of unsupported repair.

The physical dimensions of the repair are generally characterized in terms of *thickness*, estimated *volume,* and *shape* of the repair. Most repair materials are limited to specific thickness parameters. The thickness parameters for repair materials are also stated in the manufacturer's specification data. For example, most repair materials are not formulated to be troweled to a feathered (thin) edge. In such cases, the manufacturer will stipulate a minimum thickness.

Damage Condition Assessment Worksheet

Date: ____________

Location:

- District: ______________________
- County: ______________________
- Road: ______________________
- Structure #: ________________

Structure Type: ____

Description of Damage: ____

Name of Surveyor: ___________________________

Geometry

A - Orientation

9 Horizontal

9 Vertical

9 Overhead

9 Slab on Grade

B - Physical Dimensions

- Thickness: Minimum = _________ mm
  Maximum =_________ mm
- Volume (approximate) = _________ m^3
- Shape

  9 Predominately thin with a large surface area to volume ratio

  9 Predominately confined such as a void:

  9 Other (description):____________________________________
  ____
  ____

Figure 5.1 Damage Condition Assessment Worksheet (Page 1 of 4)

Substrate Condition

A Soundness

9 Testing Not Needed

9 Testing Recommended

  9 Sounding by Hammer (attach results)

  9 Pull-off Testing by ACI-503R (attach results)

B Strength

9 Testing Not Required

9 Testing Required (attach results)

  9 Nondestructive Testing (NDT) ref. ACI-228.1R

  9 Compressive Strength Testing of Concrete Cores, ACI-437R

C Cleanliness

9 Clean: requires no cleaning

9 Lightly soiled or weathered: requires minimum to moderate cleaning without concrete removal

9 Heavily soiled or weathered: requires substantial cleaning and possible concrete removal

9 Contaminated: requires analysis to determine type and degree of contamination, and may require cleaning and concrete removal, ASTM-C 856

9 Burned: requires analysis to determine extent of damage, cleaning, and possible concrete removal

9 Other: Conditions not addressed above: ______________________

____

D Moisture Conditions

9 Submerged

9 Continuously wet

9 Saturated surface dry (SSD)

9 Dry

E Condition of Reinforcement

9 Testing to determine if corrosion is occurring is not required

9 Testing required in accordance with ASTM-C876 and ASTM-C1152

9 Visual examination of reinforcement required

  9 Corrosion with little to no loss of reinforcement cross section

  9 Corrosion with loss of reinforcement cross section

  9 Physical damage not caused by corrosion

Figure 5.1 (continued) Damage Condition Assessment Worksheet (Page 2 of 4)

Structural Significance

- 9 Aesthetic — purely cosmetic surface repair
- 9 Reestablishing clear cover — Repair work not intended to reestablish lost capacity
- 9 Strengthening required — repair work required to carry both dead and/or live load conditions

Work accessibility

- 9 Access not limited
- 9 Access limited
  - 9 Traffic control required
  - 9 Repair work is in or over the vicinity of traffic
  - 9 Time limitations, rapid setting, and strength gaining materials required
  - 9 Specialized repair techniques required: ____________________

    ____

    ____

Environmental Conditions

A During Repair

1 — Temperature

- 9 Hot > 32 ° C
- 9 Moderate 10 ° C - 32 ° C
- 9 Cold < 10 ° C

2 — Moisture Level

- 9 Dry: arid
- 9 Wet: Moisture provided by rainfall or humidity
- 9 Excessively wet to submerged: within the wick zone, splash/tidal zone or below water level

B In Service

1— Temperature Ranges

- 9 Hot > 32 ° C
- 9 Moderate 10 ° C - 32 ° C
- 9 Cold < 10 ° C
- 9 Freeze thaw cycles — provide average annual # of cycles: ____

Figure 5.1 (continued) Damage Condition Assessment Worksheet (Page 3 of 4)

2 — Moisture level

9 Dry: arid

9 Wet: moisture provided by rainfall or humidity

9 Excessively wet to submerged: within the wick zone, splash/tidal zone or below water level

3 — Chemical Exposure (chlorides, etc.)

9 Yes, type(s): ____________________________

9 No

4 — Exposure to Abrasive Forces

9 Yes, type(s): ____________________________

9 No

Aesthetic Finish

9 Not required

9 Required, provide finish and color requirements: __________

____

____

____

Additional Comments & Notes

____

____

____

____

____

____

____

____

____

Figure 5.1 (continued) Damage Condition Assessment Worksheet (Page 4 of 4)

The volume and shape of the repair should be approximated to help with the estimation of cost and to help in identifying possible compatibility concerns. Generally, as the volume of the repair material increases in conjunction with various shapes that may lack confinement, the concern for ensuring compatibility increases. Also, large volume repairs may be good candidates for use of a portland cement concrete mixture, which can provide cost savings.

5.2.2 Substrate Conditions

A properly prepared substrate is one of the single most important steps in performing a successful concrete repair. It is also one of the most expensive aspects of concrete repair. The engineer must have a thorough understanding of the condition of the substrate in order to select a proper repair material and to accurately estimate the cost of the repair. There are five primary categories to characterize the substrate condition:

1. *Soundness* — The soundness of the substrate concrete is a measure of the overall condition of the concrete with respect to normal or "good" concrete. There is not a standard measure for soundness; consequently, it can be described according to various characteristics, such as various measures of strength and durability. In Chapter 4, "Condition Assessment," the tensile strength of the concrete is recommended as a good measure of soundness for repair work. There are also various ways of measuring tensile strength. Test method ACI-503R, "Direct Pull-Off Test," is recommended herein because of its field adaptability.

   Direct pull-off testing can be used to identify the condition of the substrate for damage assessment by testing both the suspect and undamaged regions. Additionally, this can be used as a quality assurance tool by stipulating the required tensile strength level of the prepared surface before application of the repair material. The engineer can define in the repair specifications the level of quality assurance testing that will be required.

2. *Strength* — When the damage to the structure is suspected to have caused a loss of structural capacity and structural analysis is deemed necessary, the structural engineer will normally need to know the actual strength of the concrete. There are various nondestructive methods that can be used as a qualitative measure and, under certain conditions, quantitatively. These methods are described in ACI-228.1R, "In-place Methods to Estimate Concrete Strength, Part 2."

   Depending on the level of confidence that is required by the engineer, these methods may suffice for actually estimating the strength. However, such nondestructive techniques are normally used only to help identify the suspect regions and to establish quadrants of uniformity. These quadrants can then be sampled by coring or by using other acceptable methods for strength testing.

Guidelines for determining the appropriate number of strength specimens to obtain can be found in ACI-437R, "Strength Evaluation of Existing Concrete Buildings, Part 3," and in the pertinent reference specifications and standards noted therein.

3. *Cleanliness* — The cleanliness of the substrate concrete can normally be determined visually. However, sometimes petrographic or chemical evaluation needs to be performed for proper verification. Six categories for describing the level of cleanliness are included in the worksheet:

   a) Clean: Requires no cleaning
   b) Lightly Soiled or Weathered: Requires minimum-to-moderate cleaning without concrete removal
   c) Heavily Soiled or Weathered: Requires substantial cleaning and possibly some concrete removal
   d) Contaminated: Requires analysis to determine type and level of contamination and will possibly require concrete removal
   e) Burned: Requires cleaning and possible concrete removal
   f) Other: Conditions not addressed above

   There are many methods for cleaning and removing concrete. Often wire brushing or high-pressure spraying with water is sufficient. When stronger cleaning methods are required or partial-to-full-depth concrete removal is necessary, there is a wide range of techniques that can be utilized. A good reference source for this information is *Concrete Repair and Maintenance Illustrated (4).*

4. *Moisture Condition* — The moisture condition of the substrate at the time of repair can influence the bond of the repair material. For example, many cementitious repair materials bond best to substrates in a saturated-surface dry condition. For most repair materials the manufacturer's specification data sheet will stipulate the permissible moisture conditions of the substrate at the time of repair *(12, 13).* Three categories of moisture conditions are used in the worksheet:

   a) Extremely Dry: Arid environmental conditions
   b) Moderate to Wet: Moisture supplied only by rainfall or humidity
   c) Excessively Wet or Submerged: Regions within the wick zone or below water level

5. *Condition of Reinforcement* — A thorough examination of the mild and active reinforcement in the damaged region should be conducted. Corrosion is an indicator of poor concrete conditions and/or contamination from chemicals such

as chlorides. The extent of the corrosion should be assessed to determine if the load-carrying capacity has been compromised. Reinforcement damaged by other causes, such as by vehicular impact, should be documented and a structural analysis performed. Three categories for characterizing the condition of the reinforcement are used in the worksheet:

a) Corrosion with little to no loss of cross section
b) Corrosion with loss of cross section
c) Physical damage to reinforcement not associated with corrosion

5.2.3 Structural Significance

The majority of concrete repairs performed by the department are not structural in nature; that is, the repair is not intended to significantly re-establish lost structural capacity. Ordinarily, repair work is conducted to re-establish protection of the reinforcement and for aesthetic purposes. This does not necessarily mean that the repair work will not be subjected to loads. In fact, most repairs will experience some level of applied loading or internal stresses caused by differences in the dimension compatibility between the repair material and substrate. There are, however, some repairs that are performed to re-establish some or all of the lost structural capacity.

By strict definition, any loss of cross-sectional area or weakening of any constituent material of the structure constitutes a loss of structural capacity. Engineering judgment plays a significant role in determining when this loss of capacity is a concern. While there are certainly discrete and isolated types of damage and repairs required simply for improving aesthetics that do not constitute any structural concerns, review by a structural engineer for repairs to structural concrete is recommended. Three categories for characterizing structural significance are used in the worksheet:

1. Aesthetic — Purely cosmetic surface repair
2. Re-establishing Clear Cover — Repair work not intended to re-establish lost capacity
3. Strengthening Required — Repair work that may engage both dead and/or live load conditions

5.2.4 Work Accessibility

Limitations of access to the damaged region often dictate the type of repair material and application technique that can be used. For example, in areas where traffic conditions severely limit the time available for performing a safe and lasting repair, a rapid setting material may be required. If the same repairs are in an overhead position, pneumatically applying the repair material may be the only viable application technique. Other factors that may influence access or that impact cost, such as traffic control, should be noted.

5.2.5 Environmental Conditions

The environmental conditions at the job site can impact both the repair process and the performance of the in-service repairs. Most repair materials are formulated for application in certain types of environments. This information is provided on the manufacturer's specification data sheet. The sensitivity of a repair material to environmental conditions is also normally addressed by the manufacturer in the specification data. However, this information is often identified in relationship to various durability measures and is not always complete or easily understood. This often is not a significant concern, as the repair material in many cases will easily provide better durability characteristics than the concrete being repaired.

When the repair work is to be performed in an aggressive environment and good durability of the repair material is necessary, the manufacturer should be able to supply performance data applicable to the anticipated environmental conditions. If this is not the case, then the material probably should not be used. Alternatively, other reference sources may provide enough information for making a selection. As a final resort, selected durability testing can be performed. This type of testing is both expensive and time consuming. A good reference source for the general performance characteristics of the five repair material categories can be found in *Concrete Repair and Maintenance Illustrated (4).*

The primary environmental factors that can affect the repair process are temperature and substrate moisture conditions. Once the repair material is applied and properly cured, the primary environmental factors of concern are temperature, moisture levels, exposure to chemicals, and abrasive forces.

5.2.6 Repair Aesthetics

Many — but not all— repair materials are formulated to provide a pleasing aesthetic finish for concrete. If an aesthetic finish is required, then the color and other surface finish characteristics should be noted.

CHAPTER 6. REPAIR MATERIAL APPLICATION TECHNIQUES

6.1 BACKGROUND

For most types of concrete repair there is generally one application technique that is best suited for ensuring a high quality and economical repair. Deciding on the best technique is normally a straightforward process, insofar as limiting factors often preclude many of the possible choices. In this procedure, it is recommended that the application technique(s) first be decided upon before selecting the repair material. By doing so, the repair material choices are limited to those materials that are formulated for the chosen application technique.

6.2 APPLICATION TECHNIQUES

The following four repair material application techniques are the most commonly used techniques for concrete repair:

1. Cast-in-place (formed or nonformed)
2. Hand application by troweling or dry packing
3. Pneumatically applied (shotcrete)
4. Crack sealing

A brief description of each method with the associated material characteristics is provided below:

6.2.1 Cast-in-Place

This repair technique category includes placement of repair material by means of gravity flow or pumping into formed or unformed areas. Placement by gravity flow or pumping requires the repair material to be formulated for accommodating the required level of viscosity. Many such repair materials are formulated to accommodate the full range of viscosity from low-slump gravity flow to pumpable consistencies, while others are formulated for a single level of consistency or viscosity.

6.2.2 Hand Application

This repair technique category includes placement of repair material by troweling or dry packing. The consistency for hand application repair materials also varies. However, this application technique is generally performed with stiff material. For *troweling*, the repair material is normally placed in lifts until the required thickness is obtained. The consistency of the repair material is adjusted depending on the orientation of the repair. Many such materials are specifically formulated with lightweight fillers to reduce sagging caused by gravity. The permissible depth of application varies significantly with the type of material, substrate condition, and orientation of the repair.

Dry packing is a placement technique used for filling confined areas. The repair material is mixed with the minimum amount of water or liquid additive necessary to provide for proper hydration or chemical reaction. For proper placement and densification, the material has to be compacted with a tamp and hammer. The intent is to provide a dense repair with low permeability. While there are no thickness limitations for this procedure, it is a very labor-intensive process.

6.2.3 *Pneumatically Applied*

This repair technique category includes placement of repair material by both the dry and wet mix methods. Pneumatically applied or "shotcrete" is a technique by which the repair material is shot through a nozzle with air pressure onto the repair surface. The repair material constituents can be supplied to the nozzle in a dry state and mixed with water at the nozzle, or a premixed material can be used. This technique allows for good densification of the material into the substrate, ease of placement for large volumes of material, placement in vertical and overhead orientations, and minimum forming requirements. The permissible depth of application varies significantly with the type of material, substrate condition, and orientation of the repair.

6.2.4 *Crack Sealing*

This repair technique category includes crack repair by three different methods: 1) rout and seal, 2) gravity flow, and 3) pressure injection. The first method of crack sealing involves routing the crack to a sufficiently large opening so the repair mortar or grout can be placed in the opening. The second method simply involves flowing enough repair material into the crack to adequately fill and seal the crack. The final method, pressure injection, involves surface sealing the crack and injecting the crack with epoxy or other specially formulated polymers.

CHAPTER 7. SELECTION OF A REPAIR MATERIAL CATEGORY

7.1 DEVELOPMENT OF A SELECTION INSTRUMENT

The next step in choosing a repair material is to select a candidate repair material category. This is referred to as a "candidate" category because it is not uncommon to have more than one viable repair material identified in a different category. Many repairs can actually be performed successfully with different types of repair materials. Sometimes the final material selection is simply based on personal preferences, while in other instances there may be only one type of repair material that satisfies all performance requirements. By accurately identifying the performance requirements and selecting the repair material application technique, the number of choices for the proper material category can be reduced.

In Chapter 6, we described four repair material application techniques. The first two techniques, cast-in-place and hand application, are the most commonly used techniques in concrete repair. Consequently, the majority of repair materials are formulated for these applications. The worksheets shown in Figures 7.1 and 7.2 have been developed to aid the engineer in the selection of the appropriate material category for these application techniques. The remaining two application techniques, pneumatically applied and crack sealing, are not as commonly used and/or have a significantly lesser number of proprietary repair materials available for use. For such application techniques, it is recommended that performance-based specifications be developed.

Repair Material Selection Worksheet

Cast-in-Place (formed or nonformed)

Material Categories: HCC, LMC, MP, MMA-PC, EPC

Performance Requirements

Safety and Economic Considerations

Requirements	Measures	Material Categories
A — Risk associated	☐ Low	Not applicable
	☐ High	Not applicable
B — Cost	☐ Low cost preferred	HCC
	☐ Cost not a limiting factor	HCC, LMC, MP, MMA-PC

Physical Characteristics

Requirements	Measures	Material Categories
* A — Thickness	☐ 6mm – 13mm	HCC, LMC, MMA-PC, EPC
	☐ 13mm – 19mm	HCC, LMC, MMA-PC, EPC
	☐ 19mm - 50mm	HCC, LMC, EPC
	☐ > 50mm	HCC, LMC, MP
* B — Shape	☐ Thin repair with large surface-area-to-volume ratio	HCC, LMC, MP, MMA-PC, EPC
	☐ Confined area with low surface-area-to-volume ratio	HCC, LMC, MP
C — Volume	☐ $\geq 1M^3$ — consider normal HCC mix design for other than thin repairs	HCC, LMC, MP
	☐ $< 1M^3$	HCC, LMC, MP, MMA-PC, EPC

Figure 7.1 Repair Material Selection Worksheet

Dimensional and Environmental Capability

Requirements	Measures	Material Categories
* A — Soundness	☐ Substrate is found to be sound by pull-off testing (ACI-503R) with average pull-off values ≥ 1.5 MPa, or by other method deemed acceptable by engineer	HCC, LMC, MP, MMA-PC, EPC
	☐ Soundness of substrate is questionable with pull-off testing (ACI-503R) values found to be < 1.5 MPa	HCC, LMC
* B — Substrate	☐ Submerged or continuously wet	HCC
	☐ Other	HCC, LMC, MP, MMA-PC, EPC
* C — Durability	☐ Extreme environmental and/or chemical exposure	MMA-PC, EPC
	☐ Other	HCC, LMC, MP, MMA-PC, EPC

User Requirements

Requirements	Measures	Material Categories
* A — Setting Characteristics	☐ Rapid	MP, MMA-PC, EPC
	☐ Normal	HCC, LMC
* B — Placement	☐ Pumpable	HCC, LMC
	☐ Gravity Flow	HCC, LMC, MP, MMA-PC, EPC
	☐ Preplaced aggregates	HCC, MMA-PC
* C – Curing Limitations	☐ Site conditions permit any type of required curing technique	HCC, LMC, MP, MMA-PC, EPC
	☐ Curing not possible	MP, MMA-PC, EPC

Figure 7.1 (continued) Repair Material Selection Worksheet

User Requirements (Continued)

Requirements	Measures	Material Categories
D — Stipulations	☐ Mixes with water	HCC, LMC, MP
	☐ Easy clean-up	HCC, LMC, MP
	☐ Low odor	HCC, LMC
	☐ Good availability	HCC, LMC, EPC
	☐ No safety concerns in addition to what is expected with normal concrete	HCC, LMC
E — Aesthetics	☐ Match substrate	HCC, LMC
	☐ Not required	HCC, LMC, MP, MMA-PC, EPC

To select a candidate material category:

1. The Performance Requirements preceded by an asterisk (*) are direct measures that have to be satisfied by the selected material category. The user should first determine which material category or categories are indicated by a check mark in all of the performance requirements identified with an asterisk.
2. If no single material category satisfies all the direct measure performance requirements, then select the material category or categories that most frequently satisfied the direct measure performance requirements and go to Step 5. Note: In this situation the user should exercise caution in the final material selection process to ensure that all the repair performance requirements can be met.
3. If a single material category satisfies all the direct measure performance requirements, that category should provide the necessary performance characteristics for the required repair work. The user can move directly to final material selection. However, verification that the material category also satisfies the remaining indirect performance requirements is recommended. Go to Step 5.
4. If multiple material categories satisfy all the direct measure performance requirements, go to Step 5.
5. The indirect measure performance requirements represent desirable material characteristics or provide recommendations. These measures can be used to help isolate the most appropriate material category. Of the material category or categories selected in Steps 1-4 above, choose a single category that best satisfies the indirect measure performance requirements.

Figure 7.1 (continued) Repair Material Selection Worksheet

Repair Material Selection Worksheet
Hand Application by Troweling or Dry Packing
Material Categories: HCC, LMC, EPC

Performance Requirements

Safety and Economic Considerations

Requirements	Measures	Material Categories
A — Risk associated with	☐ Low	Not applicable
	☐ High	Not applicable
B — Cost	☐ Low cost preferred	HCC
	☐ Cost not a limiting factor	HCC, LMC, EPC

Physical Characteristics

Requirements	Measures	Material Categories
* A — Thickness	☐ ≥6mm	HCC, LMC
	☐ 4mm – 13mm	EPC (without aggregate extension)
	☐ 4mm - 50mm	EPC (properly extended with aggregate)
* B — Shape	☐ Thin repair with large surface	HCC, LMC, EPC
	☐ Confined area with low surface-area-to-volume ratio	HCC, LMC

Figure 7.2 Repair Material Selection Worksheet

Dimensional and Environmental Compatibility

Requirements	Measures	Material Categories
* A — Soundness	☐ Substrate is found to be sound by pull-off Testing (ACI-503R) with average pull-off values ≥ 1.5 MPa, or by other method deemed acceptable by engineer	HCC, LMC, EPC
	☐ Soundness of substrate is questionable with pull-off testing (ACI-503R) values found to be < 1.5 MPa	HCC, LMC
* B — Substrate	☐ Wet in excess of SSD conditions	EPC
	☐ Other	HCC, LMC, EPC
* C — Durability	☐ Extreme environmental and/or chemical exposure	LMC, EPC
	☐ Other	HCC, LMC, EPC

User Requirements

Requirements	Measures	Material Categories
* A — Setting	☐ Rapid	EPC
	☐ Normal	HCC, LMC
* B — Bond	☐ Excellent bond required	LMC, EPC
	☐ Good bond required	HCC, LMC, EPC
* C — Curing	☐ Site conditions permit any type of required curing technique	HCC, LMC, EPC
	☐ Curing not possible	EPC

Figure 7.2 (continued) Repair Material Selection Worksheet

User Requirements (Continued)

Requirements	Measures	Material Categories
D — Stipulations	☐ Mixes with water	HCC, LMC
	☐ Ease of troweling	HCC, LMC
	☐ Easy clean-up	HCC, LMC
	☐ Low odor	HCC, LMC
	☐ Good availability	HCC, LMC, EPC
	☐ No safety concerns in addition to what is expected with normal concrete	HCC, LMC
	☐ Non-sag qualities	LMC
E — Aesthetics	☐ Match substrate	HCC, LMC
	☐ Not required	HCC, LMC, EPC

To select a candidate material category:

1. The Performance Requirements preceded by an asterisk (*) are direct measures that have to be satisfied by the selected material category. The user should first determine which material category or categories are indicated by a check mark in all of the performance requirements identified with an asterisk.
2. If no single material category satisfies all the direct measure performance requirements, then select the material category or categories that most frequently satisfied the direct measure performance requirements and go to Step 5. Note: In this situation the user should exercise caution in the final material selection process to ensure that all the repair performance requirements can be met.
3. If a single material category satisfies all the direct measure performance requirements, that category should provide the necessary performance characteristics for the required repair work. The user can move directly to final material selection. However, verification that the material category also satisfies the remaining indirect performance requirements is recommended. Go to Step 5.
4. If multiple material categories satisfy all the direct measure performance requirements, go to Step 5.
5. The indirect measure performance requirements represent desirable material characteristics or provide recommendations. These measures can be used to help isolate the most appropriate material category. Of the material category or categories selected in Steps 1-4 above, choose a single category that best satisfies the indirect measure performance requirements.

Figure 7.2 (continued) Repair Material Selection Worksheet

7.1.1 Using the Worksheets

To use the repair selection worksheet for cast-in-place or hand application shown in Figures 7.1 and 7.2, the user needs to have the completed damage condition assessment worksheet shown previously in Figure 5.1. The selection worksheets are designed as checklists that are divided into four categories:

1. Safety and economic considerations
2. Physical characteristics
3. Dimensional and environmental compatibility
4. User requirements

The *Safety and Economic Considerations* category addresses the owner's risk associated with the repair and the importance of cost in deciding what type of repair material should be used. While the "risk" is not a direct indicator for selecting a material category, understanding that the repair work poses either low or high risk to the owner helps throughout the remainder of the worksheet by putting each question into proper perspective. As previously discussed, cost should be considered a priority only in the selection process when the risk is considered low or when it is otherwise justified by value engineering.

The *Physical Characteristics* category describes measurable parameters that are direct indicators for selecting a material category. To illustrate, MP materials cannot be used in repairs less than 19 mm in thickness *(13)*. If a given repair condition has areas to be repaired that are less than 19 mm, then MP materials can be ruled out. Direct indicators are signified by an asterisk.

The *Dimensional and Environmental Compatibility* category addresses compatibility in terms of soundness and durability with respect to environmental service conditions. As addressed in Chapter 4 (Section 4.3.2), direct pull-off testing is recommended for measuring the soundness of the substrate. The pull-off test strength values noted herein are given as recommended values that are conservative to the owner. They do not have to be used as absolute values. Deviation from these values increases the risk of premature failure unless the difference in compatibility between the repair material and substrate is correspondingly reduced by proper material selection.

The concern for durability is not emphasized in the guideline. This is because most repair materials are normally going to provide better durability than the concrete. As shown in the worksheets, an exception to this is taken only for extreme conditions. The measures in this category are direct indicators for selection.

The final category, *User Requirements*, addresses specific concerns for the owner and contractor regarding aspects such as proper mixing, placement, and curing of the material.

Some of these measures are direct indicators for selection, while others are indirect measures for specialized preferences.

Place a check by each measure shown on the worksheet that describes a condition or desired characteristic of the repair. After the worksheet is completely filled out, follow the steps shown below for selecting a material category:

7.1.2 Material Category Selection Criteria

1. The Performance Requirements proceeded by an asterisk (*) are the direct measures that have to be satisfied by the selected material category. The user should first determine which material category or categories are indicated by a check mark in all of the performance requirements identified with an asterisk.
2. If no single material category satisfies all the direct measure performance requirements, then select the material category or categories that most frequently satisfy the direct measure performance requirements and go to Step 5. Note: In this situation the user should exercise caution in the final material selection process to ensure that all the repair performance requirements can be met.
3. If a single material category satisfies all the direct measure performance requirements, that category should provide the necessary performance characteristics for the required repair work. The user can move directly to final material selection. However, verification that the material category also satisfies the remaining indirect performance requirements is recommended. Go to Step 5.
4. If multiple material categories satisfy all the direct measure performance requirements, go to Step 5.

The indirect measure performance requirements represent desirable material characteristics or provide recommendations. These measures can be used to help isolate the most appropriate material category. From the material category or categories selected in Steps 1–4 above, choose a single category that best satisfies the indirect measure performance requirements.

7.2 FINAL REPAIR MATERIAL SELECTION

The final material selection process is left to the engineer so that engineering judgment can be used for selecting a repair material that bests satisfies the specific requirements of the repair. As opposed to an approved list of materials or a "cookbook" material selection methodology, this approach allows the engineer to consider the most current state-of-the-art materials that are available.

The guideline should direct the engineer to a material category based on the type of binder that will increase the probability of selecting a repair material that meets the necessary performance requirements for ensuring a long-lasting and economical repair. This does not mean that an acceptable repair material cannot be found in the other material categories. It must be recognized that there are a vast number of different types of repair materials that cannot be completely addressed by one material selection guideline. In addition, the guideline does not address all the performance requirements identified in the damage condition assessment (DCA) worksheet. This addresses only the key items necessary for isolating a material category without becoming too laborious in the process. The following steps are recommended for aiding the engineer in making the final material selection.

7.2.1 Final Material Selection Criteria

1. Identify a material category candidate as addressed in Section 7.1.
2. Identify at least two reputable repair material manufacturers and get their most current product manuals. Because the material categories are based on the type of binder, the manufacturer's product manual should have similar repair material categories. If this is not the case, contact the manufacturer for guidance.
3. Identify potential repair materials that meet the performance requirements identified on the DCA worksheet. To accomplish this, compare the repair material specification datasheet with the DCA worksheet. If the material specification data sheet does not address all the performance requirements addressed on the DCA worksheet, contact the manufacturer's technical data services and obtain the information. If the information is still not available, testing may be required; however, it is recommended that a different material be selected, if possible.
4. Discuss the potential repair materials with a *technical* sales representative. If properly qualified, these individuals can give excellent additional insight into the qualities and characteristics of the materials that can only be obtained by actually working with the material.
5. Once a candidate material has been selected, depending on the size of the project and the associated risk, prescreening testing of the repair material may be advisable. Samples of the material can be tested for verification that the material meets the reported performance data shown in the product literature.

7.3 SPECIFICATIONS AND QUALITY CONCERNS

The best repair materials will not adequately perform as intended if not properly mixed, applied, and cured or if the substrate is not properly prepared. The advances in the repair material industry have resulted in the development of many technologically sophisticated repair materials. The technical nature of these materials combined with the laborious requirements of good concrete repair, provide ample opportunity for construction mistakes that can lead to poor quality repairs. As a result, establishing good specifications for concrete repair is vital.

The three primary areas of concrete repair that should be addressed in the specification are substrate preparation, material requirements, and application requirements. This research project focused on the importance of having a sound substrate. The relationship between the relative soundness of the substrate and the dimensional compatibility of the repair material has been illustrated. The field evaluation program clearly demonstrated that the poor performing concrete repairs were normally found in association with unsound substrates. This emphasizes the need to improve the quality of substrate preparation performed on department projects. Because the quality or soundness of the substrate is difficult to assess and the preparation process is the most labor intensive activity of concrete repair, the repair specification should clearly identify the expected level of soundness and stipulate how this is to be measured. Based on this research, ACI-503R, "Direct Pull-Off Test," is recommended as one possible method for this purpose. There are other methods that can be used independently or with ACI 503R.

The importance of proper repair material selection is the basis of this research project. Proper selection of a good quality proprietary repair material provides the engineer with the needed material performance properties, technical guidance, and often some level of product warranty. However, many of these materials are not easy to work with and often require a high level of expertise for use of the material as described by the manufacturer. The expectations that the repair materials be properly mixed, applied, and cured in accordance with the manufacturer's recommendations must be stipulated. It is also recommended that before the repair work is performed, the contractor should demonstrate the ability to use the repair material properly. If a repair material is not specified and the contractor is given the option of selecting the repair material, then it should be stipulated that the repair material shall be approved by the engineer and that prequalification testing may be required. Finally, some level of periodic job control material testing should be required to ensure consistent quality of the repair material and construction practices.

The final aspect of a comprehensive repair specification is stipulating that the repair material is properly applied and cured. Inspection and in-situ testing is recommended. It should be stipulated that visual inspection for ensuring proper procedures be conducted, and that testing of the in-place repair work be performed. The type of testing, frequency of testing, and acceptance values should be included.

Performance-based specifications are frequently used in the concrete repair industry. In addition, some of the material manufacturers provide training and certification for contractors. Owners can stipulate that the contractor must be certified to use certain materials and application procedures before becoming a qualified bidder.

As demonstrated, there are many approaches that can be used to develop a specification. The most important factor is to clearly delineate the quality requirements of the repair material and construction practices, including the methods for demonstrating that these requirements are satisfied.

CHAPTER 8. CONCLUSIONS

8.1 SUMMARY

The Texas Department of Transportation (TxDOT) is confronted with the monumental task of maintaining an extensive concrete infrastructure that is beginning to age and deteriorate. Maintenance of the transportation infrastructure is requiring more frequent and extensive levels of restoration. As repair material technology advances to meet the needs of organizations such as TxDOT, so does the difficulty of selecting the right repair material. To begin addressing this concern, TxDOT funded this research project to establish a consistent approach to effective repair material selection.

Project 0-1412, "Repair of Structural Concrete," was conducted in three phases. The first phase consisted of a comprehensive literature search to identify the state of the art in concrete repair materials, application techniques, and material selection. A laboratory evaluation program of various types of repair materials was conducted in the second phase of the research to help isolate the pertinent material characteristics associated with good concrete repairs specific to the Texas environment. A field evaluation program was then conducted to assess and correlate the actual in-situ repair performance to that of the material properties measured in the laboratory.

The final phase of the research, the subject of this report, comprises a synthesis of the first two phases of the research and the development of a material selection guideline and recommendations for structural concrete repair. The guideline and recommendations provide the criteria for assessing the damage conditions and for determining the performance requirements of both repair application techniques and proper material selection. Emphasis was placed on developing a guideline that, when combined with sound engineering judgment, provides the basis for proper material selection.

8.2 CONCLUSIONS

By synthesizing the results of the previous phases of the research, we identified the important material characteristics associated with good concrete repair. To help minimize the number of variables in the material selection process, the different types of repair materials were categorized into five different groups based on the type of binder: hydraulic cementitious concrete (HCC), magnesium phosphate concrete (MP), epoxy polymer concrete (EPC), methyl methacrylate concrete (MMA-PC), and latex-modified concrete (LMC). Helping the engineer identify the most appropriate repair material category is the primary focus of the guideline.

The steps associated with performing a complete concrete repair process are addressed in relationship to the material selection process:

1. Condition assessment
2. Identification of performance requirement
3. Repair material application techniques

The process of conducting a condition assessment for identifying the performance requirements of the repair material is the necessary first step toward isolating the pertinent material properties. A condition assessment worksheet was developed to help the engineer with this process.

From the findings of the condition assessment the pertinent repair material performance requirements will be identified. Steps for accomplishing this process are outlined with recommendations for performing a materials investigation of the substrate concrete. A rationale for damage assessment by petrographic evaluation, chemical analysis, and physical testing by both destructive and nondestructive testing procedures is included. Direct pull-off testing in accordance with ACI-503R is recommended as one method for assessing the soundness of the substrate concrete and for measuring the bond strength existing between the repair material and substrate. A value of 1.5 Mpa is recommended as the minimum pull-off strength for the concrete soundness and bond requirements.

Selection of the repair material application technique is identified as the next step in the process. Often by identifying the application technique, many types of repair materials can be eliminated as possible choices. This is because most repair materials are formulated for specific application techniques. A description of the following four application techniques is provided to help familiarize the engineer with the most typical approaches for applying repair material: cast-in-place (formed/nonformed), hand application by troweling or dry packing, pneumatically applied, and crack sealing.

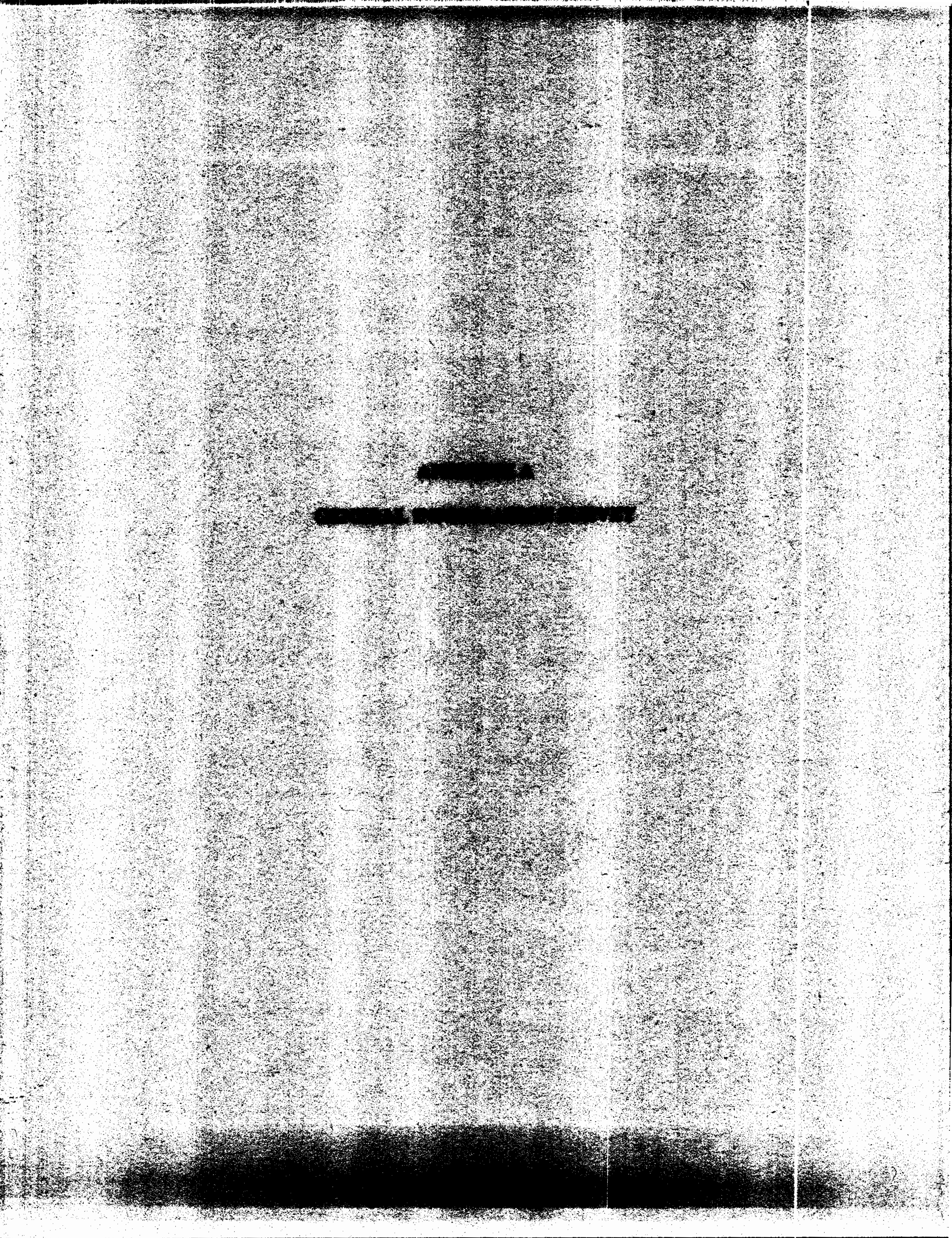
Once the application technique has been identified, the next step is to select a repair material category. The rationale for doing this is addressed in detail in Chapter 7 of this report. Worksheets have been developed to help the engineer identify the important performance requirements of the damage condition. By using the worksheets, an appropriate repair material category can be identified. Additional guidance and recommendations are provided to help the engineer make a final material selection based on the identified performance requirements of the damage condition, the selected material category, and engineering judgment.

The conclusion of Chapter 7 addresses specification development and quality concerns. The importance of good quality control and quality assurance in association with concrete repair is emphasized.

The guideline and recommendations reported herein will provide a rational and systematic approach to selecting a repair material. Because of the vast number of different types of repair materials, application techniques, and damage conditions, addressing every possible condition is not feasible. This research has established the basic framework for material selection. Significant improvements are possible through the use of automation and expert system software applications. The next logical step is to build upon and expand this research accordingly.

REFERENCES

1. Vaillant, Daniel. "Material Selection Criteria for Structural Concrete Repair," Master's thesis, The University of Texas at Austin, May 1995.
2. Traub, Daniel W. A. "Laboratory and Field Evaluation of Required Material Properties for Concrete Repairs," Master's thesis, The University of Texas at Austin, December 1996.
3. Emmons, Peter H. *Concrete Repair and Maintenance Illustrated*, R. W. Means Company, Kingston, MA, 1993.
4. Emmons, Peter H., and Vaysburd, A. M. "Compatibility Considerations for Durable Concrete Repairs," *Transportation Research Board Record 1382*. Structural Preservations Systems, Inc., 1993, pp.13–19.
5. Emmons, Peter H., and Vaysburd, A. M. "Performance Criteria for Concrete Repair Materials, Phase 1," U.S. Army Corps of Engineers.
6. Mindess, S., and Young, J. F. *Concrete*, Prentice Hall, Inc., Edgewood Cliffs, NJ, 1981.
7. "Field Test for Surface Soundness and Adhesion," ACI-503R, ACI Manual of Concrete Practice, Part 19.
8. Beer, George P., and Fowler, David W. "Results of a Survey on the Use of Rapid-Setting Repair Materials," Center for Transportation Research Report 311-1, The University of Texas at Austin, 1982, p. 31.
9. Mather, Braynt. "Concrete in Transportation: Desired Performances and Specifications," *Transportation Research Record 1382*, 1993, pp. 5–10.
10. *Aberdeen's Concrete Sourcebook.* The Aberdeen Group. April 1994–March 1995 Edition, Volume 11.
11. *Standard Specifications for Construction of Highways, Streets and Bridges*, Texas Department of Transportation, 1993.
12. Concrete Restoration Systems, Sika Products — Marketing Tool. Lyndhurst, NJ.
13. Technical Support Manual, Division 3. Master Builders, Inc., Cleveland, OH, 1996.



APPENDIX A: GENERAL INFORMATION SURVEY

THE UNIVERSITY OF TEXAS AT AUSTIN PROJECT 0-1412, "REPAIR OF STRUCTURAL CONCRETE" GENERAL INFORMATION SURVEY

DISTRICT: ______________________

Completed by: ____________________ Title: ______________ Date: ________

Address: _________________________ Telephone: __________ FAX: ________

This survey has been prepared to assess the current state of the art for repairing structural concrete. It comprises four sections. Each section has the following goals:

Section 1: Types of Repairs

- Determine the relative quantity of all types of repairs that are being made throughout Texas, the rest of the United States, and Canada

Section 2: Repair Procedures

- Confirm that the procedures being employed are similar to the procedures outlined in current literature
- Uncover new and innovative procedures

Section 3: Material Evaluation

- Gather useful information on strengths and weaknesses of proprietary repair materials

Section 4: Selection of Repair Materials

- Establish a priority list of mechanical properties and/or additional factors that need to be evaluated for various types of repair conditions

Please consider repairs to concrete bridge components (i.e., piers, abutments, decks, etc.) and include concrete overlays. Do not consider concrete pavements when responding to the questions. It is a good idea to read over the survey in its entirety prior to answering any questions.

TYPES OF REPAIRS

Concrete repairs for the purpose of this survey will be divided into three categories as follows:

Damaged Concrete: Concrete that has been damaged by external forces such as impact, fire, foundation settlement, floods, and overload

Deteriorated Concrete: Concrete that has deteriorated over a period of time due to various environmental conditions and now exhibits faults such as corrosion-induced spalling, freeze/thaw-related scaling or cracking, surface popouts, contaminated concrete, long-term shrinkage cracking, abrasion, or delaminations

Defective Concrete: Concrete that needs to be repaired because problems have since evolved owing to faulty design, construction, or materials' deficiency

1. Of all the concrete repairs being performed in your district, estimate as a percentage the amount of each type of repair being performed (total should equal 100%):

		Example:
Damaged Concrete	_____%	*42%*
Deteriorated Concrete	_____%	*28%*
Defective Concrete	_____%	*30%*

2. In cases of damaged concrete, please estimate which causes have resulted in damage that was serious enough to warrant a repair in the last 5 years and prioritize the causes in terms of frequency (1 indicates the most common type of damage):

_____ Impact Damage
_____ Fire
_____ Foundation Settlement
_____ Overload
_____ Floods
_____ Other ______________________________
____

3. Please estimate which types of deteriorated concrete have been repaired in your district in the last 5 years and prioritize the types of repairs in terms of frequency (1 is the most common):

_____ Corrosion-induced delaminations or spalling
_____ Delamination of bonded concrete overlays
_____ Freeze/thaw-related scaling
_____ Surface popouts
_____ Cracking (shrinkage, thermal, or due to reactive aggregates)
_____ Abrasions
_____ Other ______________________________
____

4. In cases of corrosion-induced delaminations or spalling of concrete, prioritize the parts of the bridge that are most commonly repaired (1 is the most common type of repair):

_____ Bridge decks
_____ Abutments
_____ Wingwalls
_____ Primary superstructure (I-girders, box beams, etc.)
_____ Bent caps and columns

5. Do you recall any instance when a field repair has been made to rectify the following?

	YES	NO
Design Error	_____	_____
Construction Error	_____	_____
Material Deficiency	_____	_____

If you answered YES to any of the above, please briefly describe the problems you have encountered:

____
____
____
____
____
____
____
____

(Please write on back or include additional information that you think may be useful.)

6. Have the repairs of *prestressed* concrete members (including concrete end coating of prestressed beams) that have been approved by the Materials and Tests Division been successful?

______ YES
______ NO

If you answered NO to the above question, please indicate what types of problems that you have experienced and briefly describe what corrective actions (if any) were taken.

____
____
____
____
____

(Please write on back or include additional information that you think may be useful.)

REPAIR PROCEDURES

1. Please estimate as a percentage the amount of concrete repairs performed in which plans and specifications are prepared vs. those done by maintenance crews without plans and specifications.

_____ Repairs with Plans/Specifications (%)
_____ Repairs without Plans/Specifications (%)

2. In cases when plans and specifications are prepared, check the office(s) responsible for the preparation (check as many as apply):

_____ District Bridge Engineer
_____ District Maintenance Engineer
_____ District Construction Engineer
_____ Design Division (Austin)
_____ Private Consultant

3. What factors initiate a repair? Choose those that apply and prioritize them (1 indicates most likely to initiate a repair).

_____ The structural capacity has been reduced
_____ A routine inspection has outlined corrective maintenance procedures
_____ The appearance of the structure is not acceptable
_____ Falling concrete may cause unsafe conditions
_____ The riding surface is excessively rough
_____ Other (specify):_______________________________
____
____

4. In a situation when unacceptable concrete needs to be removed, which method is used in your district for the removal? Choose those that apply and prioritize them (1 indicates the most common type of concrete removal method).

_____ Jackhammering
_____ Sandblasting
_____ Hydrodemolition
_____ Other _______________________________
____

5. Upon removal of the unacceptable concrete, what additional work is typically done to prepare the surface (check those that apply)?

_____ Nothing (the surface is left untouched)
_____ Additional mechanical roughening (i.e., bush-hammering) is applied
_____ A bonding agent is applied
_____ Mechanical anchorage is added (i.e., dowels)
_____ Other _______________________________
____

6. If a bonding agent is typically used between the existing concrete and the repair material, please list the bonding agents that have been used in your district.

____
____
____
____

7. In situations where reinforcing bars have been partially exposed (particularly in a delaminated region), but do not exhibit any section loss, after cleaning the bars, do you apply an epoxy coating prior to patching the surface?

_____ YES
_____ NO

8. Prior to applying the patching material, the repair surface:

_____ is kept dry
_____ is wet, but not saturated
_____ is completely saturated
_____ is prepared according to the material selected

9. When it is necessary to repair cracking in concrete, which method(s) do you use (check all that apply)?

_____ Epoxy injection
_____ Methacrylate monomer (brushed on)
_____ Routing of the crack followed by a patch
_____ Other: _________________________
____

MATERIAL EVALUATION

Please complete a material evaluation for ***each*** repair material used in your district within recent years. Materials can be referred to by their brand name, and this sheet may be photocopied.

1. Name of material: ____

2. Years used in your district: From ____________ to ______________

3. Primary types of repairs:

   ____

   ____

4. Approximate amount of material used annually:

   _____ ≤ to 1,000 lb _____ 1,000 to 25,000 lb _____ > 25,000 lb

5. Rate the material by circling the appropriate number in each category:

a. COST	1	2	3	4	5	(1 LOW, 5 HIGH)
b. EASE OF PLACEMENT	1	2	3	4	5	(1 EASY, 5 DIFFICULT)
c. SHRINKAGE	1	2	3	4	5	(1 LOW, 5 HIGH)
d. DURABILITY	1	2	3	4	5	(1 LOW, 5 HIGH)
e. SETTING TIME						
Normal conditions	1	2	3	4	5	(1 SLOW, 5 FAST)
Cold conditions	1	2	3	4	5	(1 SLOW, 5 FAST)
f. APPEAL TO WORKERS	1	2	3	4	5	(1 DISLIKE, 5 LIKE)
g. BOND TO EXISTING CONCRETE						
Horizontal	1	2	3	4	5	(1 POOR, 5 GOOD)
Vertical	1	2	3	4	5	(1 POOR, 5 GOOD)
Overhead	1	2	3	4	5	(1 POOR, 5 GOOD)
Wet Surfaces	1	2	3	4	5	(1 POOR, 5 GOOD)
h. APPEARANCE	1	2	3	4	5	(1 POOR, 5 GOOD)
g. OVERALL EFFECTIVENESS	1	2	3	4	5	(1 POOR, 5 GOOD)

6. Have you ever performed any tests on the above material? YES _____ NO _____
   If yes, please provide us with a copy of the test results.

7. Please note any conditions under which this material should not be used:

   ____

   ____

SELECTION OF REPAIR MATERIALS

There are a variety of different repair situations that may be encountered in the field. For the next set of questions, please examine the following four situations:

Situation A: A vertical concrete surface needs to be patched, but the patch does not need to carry any load and the surrounding concrete is not deteriorating. *Example:* A sleepy truck driver has brushed one side of a pier and removed 2–1/2" of concrete, exposing the rebar.

Situation B: A bridge deck needs a horizontal patch because the concrete is spalling. *Example:* A bridge in an area in which deicing salts are used excessively exhibits corrosion-induced spalling and needs three patches of 3 ft–4 ft each.

Situation C: A bridge needs a vertical patch in a load-carrying member. *Example:* A precast/prestressed bridge's exterior girder has been damaged and the prestressing strands have been exposed.

Situation D: A bridge needs an overhead patch. The patching material must be chosen for both durability and strength. *Example:* The bottom of a precast box beam has been scraped by an overheight vehicle. The damaged area now exhibits rust-staining and minor flexural cracking.

1. Please prioritize the *mechanical properties* that are required of the patching material to ensure a successful repair (1 indicates most important). ***Note***: You do not need to include each factor. If you feel that some of the choices bear no importance, simply exclude them from your ranking (i.e., leave them blank).

	Situation A *(Vertical/ No Apparent Problems)*	***Situation B*** *(Horizontal/ Durability)*	***Situation C*** *(Vertical/ Strength)*	***Situation D*** *(Overhead/ Durability & Strength)*
Compressive Strength	_____	_____	_____	_____
Working Time	_____	_____	_____	_____
Flexural Strength	_____	_____	_____	_____
Bond Strength to Existing Concrete	_____	_____	_____	_____
Shrinkage	_____	_____	_____	_____
Coefficient of Thermal Expansion	_____	_____	_____	_____
Stiffness/Modulus of Elasticity	_____	_____	_____	_____
Slump/Cohesiveness	_____	_____	_____	_____
Permeability	_____	_____	_____	_____
Creep	_____	_____	_____	_____
Color	_____	_____	_____	_____
Other ________________	_____	_____	_____	_____
________________	_____	_____	_____	_____

2. In addition to the mechanical properties of the material itself, please prioritize the additional factors that would influence your choice for the situations described above (1 indicates most important). ***Note***: You do not need to include each factor. If you feel that some of the choices bear no importance, simply exclude them from your ranking (i.e., leave them blank).

3.

	Situation A *(Vertical/ No Apparent Problems)*	***Situation B*** *(Horizontal/ Durability)*	***Situation C*** *(Vertical/ Strength)*	***Situation D*** *(Overhead/ Durability & Strength)*
Material Cost	_____	_____	_____	_____
Speed of Repairs/ Interruption of Service	_____	_____	_____	_____
Manufacturer's Claims	_____	_____	_____	_____
Weather Conditions on Day of Repair	_____	_____	_____	_____
Past Experience with the Material	_____	_____	_____	_____
Method of Material Application	_____	_____	_____	_____
Other ______________	_____	_____	_____	_____
______________	_____	_____	_____	_____

3. For each of the situations described, indicate which material (you may use brand names) you would suggest to make the repair. Use the following assumptions in making your suggestions:

- Material cost is irrelevant
- The weather at the time of repair is sunny and warm (70°F)
- Traffic can be interrupted for 1 day

Situation A: ____
____

Situation B: ____
____

Situation C: ____
____

Situation D: ____
____

APPENDIX B

RESEARCH REPORT NO. [illegible] TABLES AND FIGURES

Table 2.1: Typical Physical Properties of Concrete and Repair Materials *(10)*

Property	Typical Values for Normal Concretes and Cementitious Mortars	Polymer-Modified Cementitious Mortar	Polymer Mortars
Compressive Strength	20–50 MPa (3,000–7,000 psi)	30–60 MPa (4,500–9,000 psi)	50–100 MPa (7,250–14,500 psi)
Tensile Strength	2–5 MPa (300–750 psi)	5–10 MPa (750–1,500 psi)	10–15 MPa (1,500–2,250 psi)
Modulus of Elasticity	(20–30) x 10^3 MPa (3.0–7.5) x 10^6 psi	(15–25) x 10^3 MPa (2.3–3.7) x 10^6 psi	(10–20) x 10^3 MPa (1.5–3.0 x $10^{6)}$ psi
Coefficient of Thermal Expansion	10 x 10^{-6}/°C 6 x 10^{-6}/°F	(10–20) x 10^{-6}/°C (6–10) x 10^{-6}/°F	(25–30) x 10^{-6}/°C (14–17) x 10^{-6}/°F
Water Absorption (% by weight)	5–15	1–2	0.1–0.5

Table 3.1: Texas Average Results

Repair Category	Estimated Amount	Type and Frequency (1 is the most common)
Damaged Concrete	49%	(1) Impact damage (2) Overload (3) Floods (4) Foundation settlement (5) Fire
Deteriorated Concrete	42%	(1) Corrosion-induced spalling (2) Surface popouts (3) Cracking (shrinkage, thermal, etc.) (4) Freeze/thaw-related scaling (5) Abrasions (6) Delamination of overlays
Defective Concrete	9%	

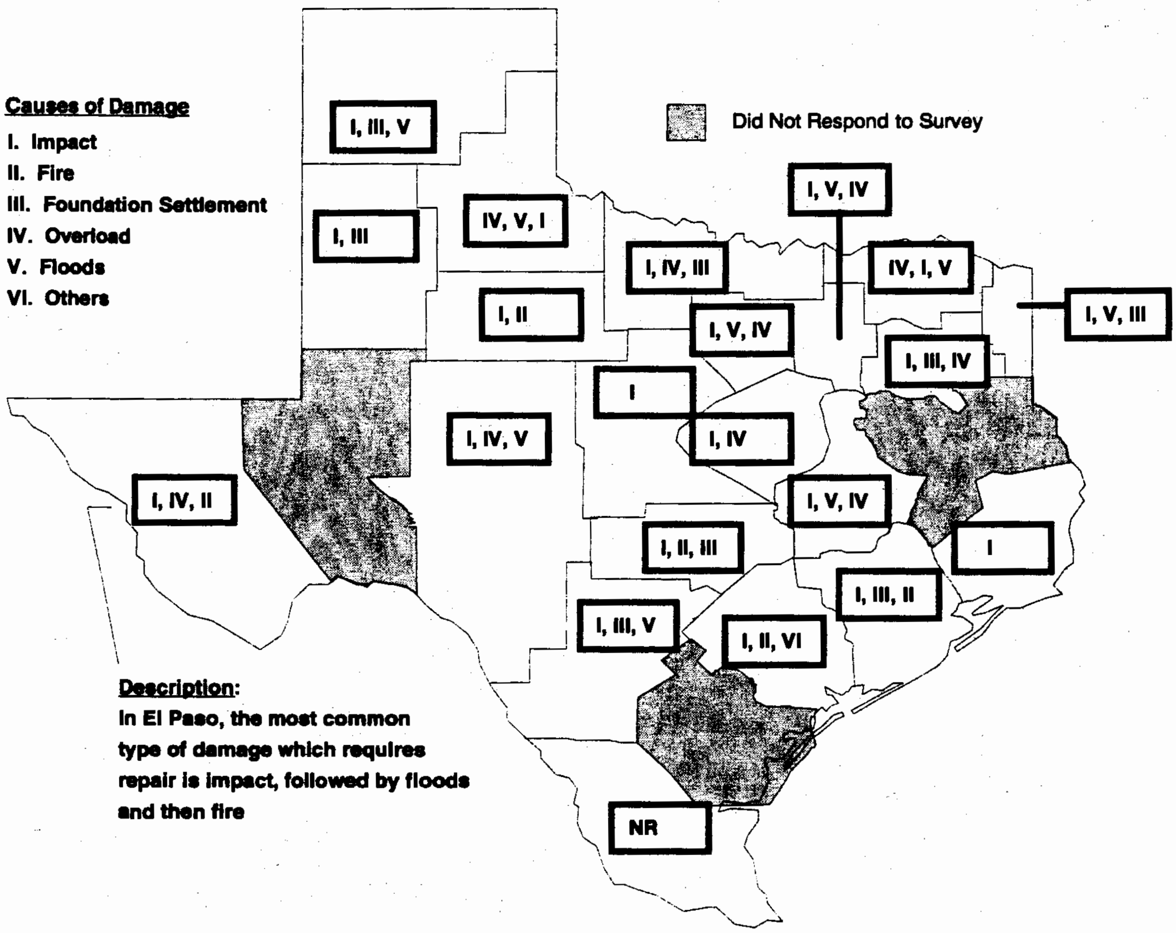


Figure 3.3: Three Most Common Types of Damage in Each District

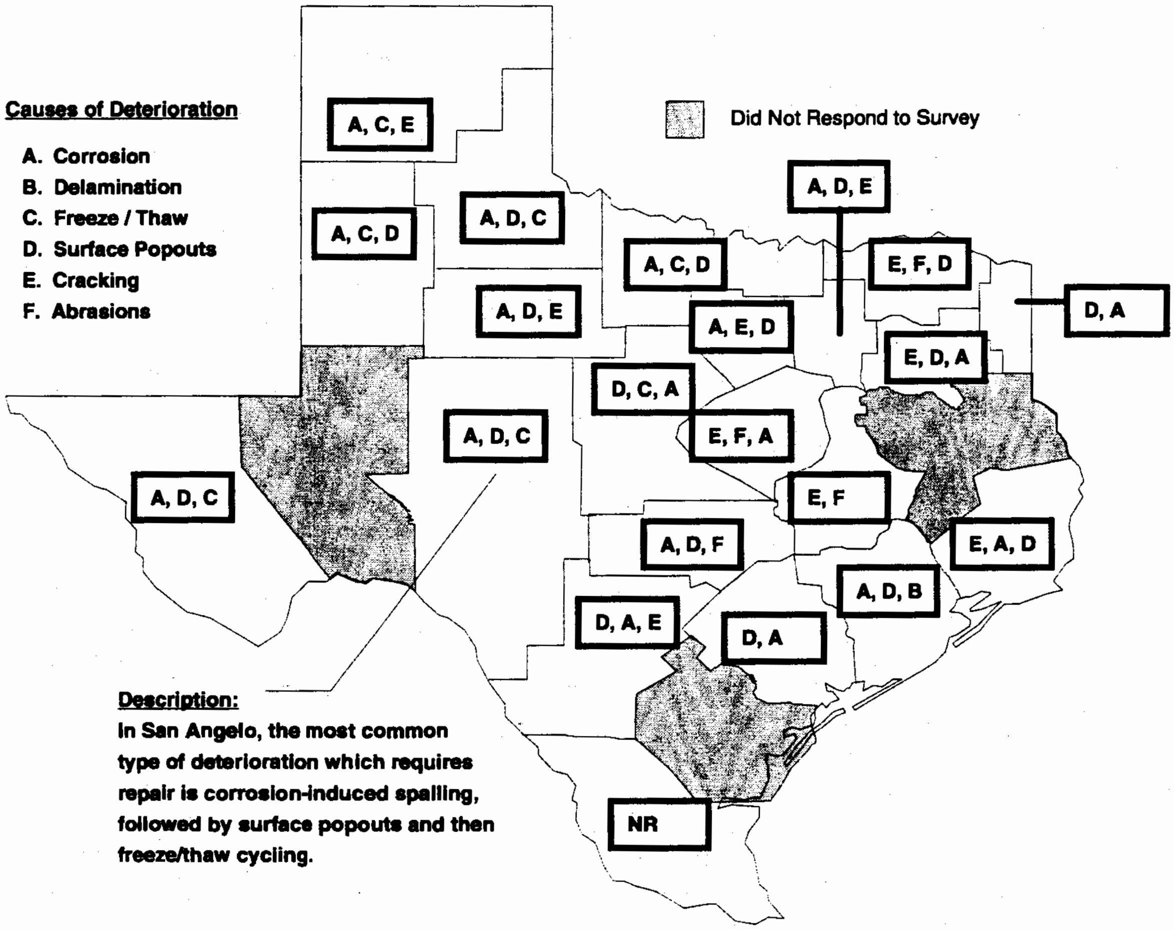


Figure 3.4: Three Most Common Types of Deterioration in Each District

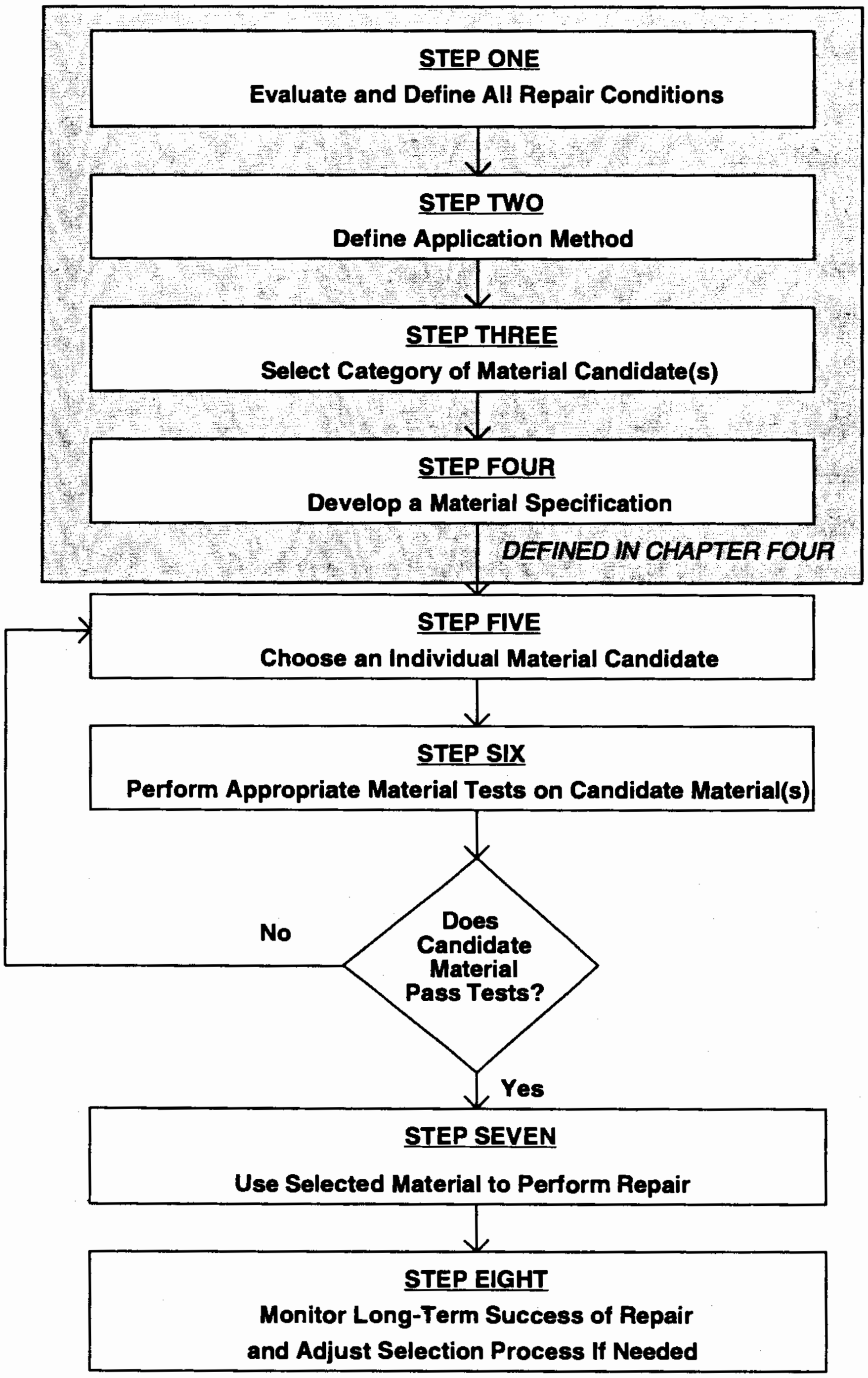


Figure 4.1: Material Selection Procedure

APPENDIX C

[illegible]

Table 3.6 Reported Material Property Values of the Proprietary Products

		PCC				MPC	Epoxy PC		MMA PC	LMC	
		Duracal		Class "K"	Emaco	Set 45	Type VIII	Burke-Epoxy	T17	Sika 122	Burke-Krete
Property	Day	Neat	Ext	Ext	Neat	Neat	Ext	Ext	Neat	Neat	Neat
Compressive Strength (MPa)	1	56	42		31	41			48	14	2.6
	3	64	47							41	
	7				62					45	16.5
	28	72	59		76	55		91	55	61	20.9
Flexural Strength (MPa)	1				5.3				14	3.4	
	3										
	7				7.9					11.7	
	28				9.0				14	13.8	
Modulus of Elasticity (X 10^4 MPa)					3.0	3.62			0.34-0.68		
Plastic Shrinkage (%)		0.20	0.05						0.2		
Drying Shrinkage (%)		0.125	0.01					0.12 mm			
Coefficient of Thermal Expansion (10^{-6})						12.8		53.4			
Bond (MPa)					2.2				100% Substrate	15.2	
Splitting Tensile					82.7					7.6	
Slant Shear					21.4	17.2 @ 14 day					
Absorption											
Abrasion									3.5 g lost		
Permeability					Very Low	Very Low*					
Freeze/Thaw		Excellent	Fair		98 %	> 80%			No Change		
Sulfate Resistance						0.1% @ 52 weeks					
Set Time (min.)		20-35	20-35							20-60	

Table 5.2 Results of Bond Strength Test

Material Type	Thickness (mm)	Initial		Final		
		Pull-Off Strength (MPa)	Failure Type	Pull-Off Strength (MPa)	Number of Thermal Cycles	Failure Type
PCC 1	19	1.6	I	2.0	840	I
	38	2.1	I	2.3		I
	76	2.3	I	2.9		I, R
PCC 2	19	2.2	R	2.5	560	I
	38	2.2	R	2.4		I
	76	1.7	I	1.9		I
PCC 3	19	1.4	I	2.5	896	I
	38	2.0	I	1.7		S, I
	76	1.1	I	2.7		I
MPC 1	19	1.7	R	1.9	784	R
	38	2.2	I, R	2.1		I, R
	76	2.4	I, R	2.0		I
Epoxy PC 1	6 (Neat)	3.7	S	Failed	728	S
	38 (Neat)	Failed	S	Failed		S
	6	3.4	S, I	3.3		S, I
	38	3.9	S, I	3.4		S
	76	2.8	S	3.2		I
Epoxy PC 2	6	2.8	S, I	3.3	280	I
	38	4.0	S	3.4		S
	76	2.7	S, I	3.2		S
MMA PC 1	6	3.8	S, I	3.7	616	I
	38	4.1	S	3.1		I
	76	3.5	I	3.3		I
LMC 1	6	3.4	S, I	3.3	1120	I
	19	3.1	S, I	3.5		I
	38	2.7	I	3.0		I
LMC 2	6	2.0	I	1.5	336	I
	19	1.0	I	0.5		I
	38	0.8	I	0.8		I

S = Substrate Failure
I = Interface Failure
R = Repair Material Failure

Table 5.7 Comparison of Material Properties by Ranking

	Material Type	Compressive Strength (High = 1)	Flexural Strength (High = 1)	Modulus of Elasticity (High = 1)	CTE (Low=1)	Initial Bond Strength (High = 1)	Absorption (Low = 1)	Abrasion (Low = 1)	Permeability (Low = 1)
PCC	PCC 1 Neat	2	13	9	4	11	13	10	8
	PCC 1 Extended	6	10	6	9	8	11	11	9
	PCC 2 Extended	12	11	5	3	9	9	7	10
	PCC 3 Neat	1	7	3	5	12	10	4	5
MPC	MPC 1 Neat	9	12	2	1	10	12	12	10
	MPC 1 Extended	5	9	1	7	7	8	13	10
Epoxy PC	Epoxy 1 Extended	11	4	12	13	3	3	2	1
	Epoxy 2 Extended	3	2	10	10	5	5	6	1
MMA	MMA 1 Neat	7	1	13	12	1	2	3	1
	MMA 1 Extended	4	3	7	11	2	1	1	1
LMC	LMC 1 Neat	10	5	8	8	4	6	9	5
	LMC 1 Extended	8	6	4	6	6	4	5	5
	LMC 2 Neat	13	8	11	2	13	7	8	10

Table 6.19 Comparison of Field Evaluation Sites

Geographic Location	Repair Material Type	Age of Repair (Years)	Structural Element(s) Repaired	Orientation	Pull-Off Strength (MPa)	Standard Deviation (MPa)
Austin No. 1	MMA	20	Bridge Deck	Horizontal	1.2	0.1
Austin No. 2	Latex-Modified	3	Bridge Deck	Horizontal	1.0	0.4
Austin No. 3	Epoxy	10	Column	Vertical	0.9	0.2
San Antonio	Epoxy	2–3 Months	Prestressed Panel	Horizontal	0.2–1.0	0.4
Amarillo	Cementitious	7–8	Pier Cap	Vertical	0.3	0.04
Fort Worth No. 1	PU Epoxy	5 5	Entrance Ramp Entrance Ramp	Horizontal Horizontal	0.5–4.2 1.3–4.1	0.0–1.6 0.1–0.9
Fort Worth No. 2	PU Epoxy	4 4	Bridge Deck Bridge Deck	Horizontal Horizontal	2.8 2.9	0.3–0.5 0.6
Wichita Falls No. 1	Latex-Modified	1	Arches, Backwalls	Vertical	0.9	0.3
Wichita Falls No. 2	Latex-Modified Cementitious	1 1	Bridge Deck Bridge Deck	Horizontal Horizontal	0.9 0.7	0.3 0.6
San Angelo	Cementitious	5	Pier Caps, Columns Backwalls	Vertical	1.0	0.4
Lufkin No. 1	Cementitious	8	Bridge Deck	Horizontal	0.9	0.2
Lufkin No. 2	Epoxy	12	Pier Cap	Vertical	0.4–3.4	1.1
Presidio	Epoxy	5	I-Beam	Vertical	Failed	N/A
Victoria	Cementitious Epoxy	1 Day to 1–1/2 Years	U-Beam U-Beam	Vertical and Horizontal	1.5–3.0 1.3–2.8	0.4–0.6 0.4–0.7

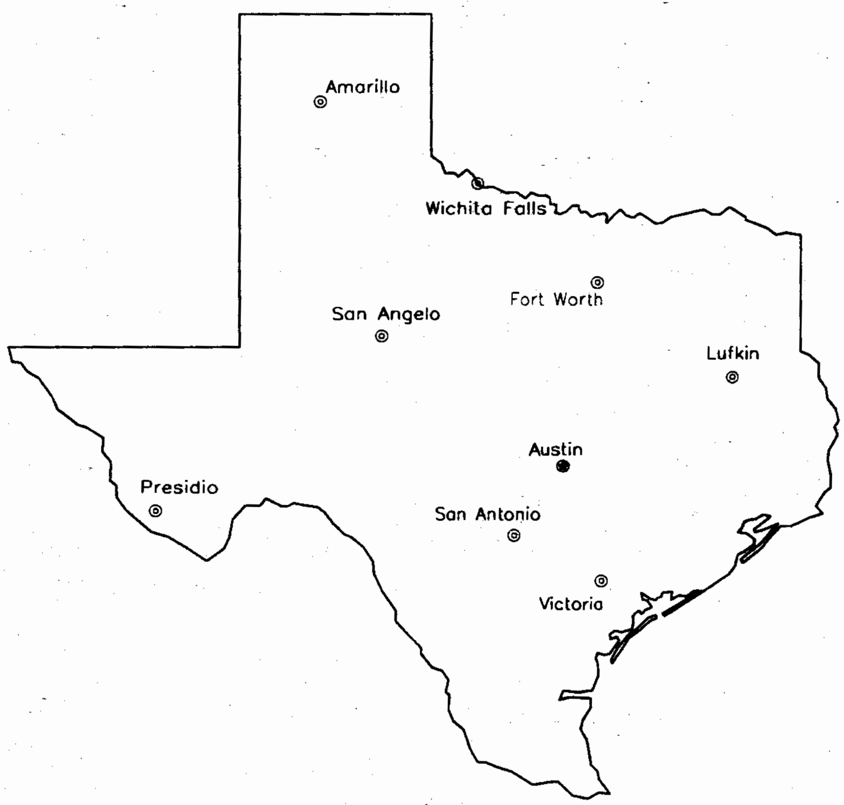


Figure 6.1 Locations Investigated During the Field Evaluation Program

Table 6.19 Comparison of Field Evaluation Sites

Geographic Location	Repair Material Type	Age of Repair (Years)	Structural Element(s) Repaired	Orientation	Pull-Off Strength (MPa)	Standard Deviation (MPa)
Austin No. 1	MMA	20	Bridge Deck	Horizontal	1.2	0.1
Austin No. 2	Latex-Modified	3	Bridge Deck	Horizontal	1.0	0.4
Austin No. 3	Epoxy	10	Column	Vertical	0.9	0.2
San Antonio	Epoxy	2–3 Months	Prestressed Panel	Horizontal	0.2–1.0	0.4
Amarillo	Cementitious	7–8	Pier Cap	Vertical	0.3	0.04
Fort Worth No. 1	PU Epoxy	5 5	Entrance Ramp Entrance Ramp	Horizontal Horizontal	0.5–4.2 1.3–4.1	0.0–1.6 0.1–0.9
Fort Worth No. 2	PU Epoxy	4 4	Bridge Deck Bridge Deck	Horizontal Horizontal	2.8 2.9	0.3–0.5 0.6
Wichita Falls No. 1	Latex-Modified	1	Arches, Backwalls	Vertical	0.9	0.3
Wichita Falls No. 2	Latex-Modified Cementitious	1 1	Bridge Deck Bridge Deck	Horizontal Horizontal	0.9 0.7	0.3 0.6
San Angelo	Cementitious	5	Pier Caps, Columns Backwalls	Vertical	1.0	0.4
Lufkin No. 1	Cementitious	8	Bridge Deck	Horizontal	0.9	0.2
Lufkin No. 2	Epoxy	12	Pier Cap	Vertical	0.4–3.4	1.1
Presidio	Epoxy	5	I-Beam	Vertical	Failed	N/A
Victoria	Cementitious Epoxy	1 Day to 1–1/2 Years	U-Beam U-Beam	Vertical and Horizontal	1.5–3.0 1.3–2.8	0.4–0.6 0.4–0.7