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7. Author(s)
Daniel W. Traub, David W. Fowler, and Ramon L. Carrasquillo

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Center for Transportation Research
The University of Texas at Austin
3208 Red River, Suite 200
Austin, Texas 78705-2650

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16. Abstract

This study investigated the material properties necessary to ensure a successful concrete repair. The information and data contained in this report will assist in the preparation of a repair material selection guideline, one that could aid engineers in the selection of the most appropriate repair material based upon the environmental conditions. The study consisted of both a laboratory evaluation program and a field evaluation program. The laboratory evaluation program identified and tested the most important repair material properties. The field evaluation program consisted of both a qualitative and quantitative evaluation of existing repairs throughout Texas. One of the primary objectives of the field visits was to investigate a wide range of typical repairs that can be expected in Texas. The two evaluation programs can be synthesized into a single set of material selection guidelines.

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Daniel W. Traub
David W. Fowler
Ramon L. Carrasquillo

Research Report 1412-2

Research Project 0-1412
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
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October 1996

IMPLEMENTATION RECOMMENDATIONS

The information and data presented in this report can be used as a guide in aiding an engineer in the concrete repair material-selection process. This report has consolidated and evaluated the pertinent material properties necessary to ensure a successful concrete repair. In addition to laboratory testing, a comprehensive field evaluation program was conducted to determine the actual in situ performance of various repair materials in different climatic conditions. Using this report, an engineer will be better equipped to:

1. properly identify the important factors of a repair and,
2. based upon material properties test results, be able to properly identify and select the most appropriate repair material.

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

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SUMMARY

This study investigated the material properties necessary to ensure a successful concrete repair. The information and data contained in this report will assist in the preparation of a repair material selection guideline, one that could aid engineers in the selection of the most appropriate repair material based upon the environmental conditions. The study consisted of both a laboratory evaluation program and a field evaluation program. The laboratory evaluation program identified and tested the most important repair material properties. The field evaluation program consisted of both a qualitative and quantitative evaluation of existing repairs throughout Texas. One of the primary objectives of the field visits was to investigate a wide range of typical repairs that can be expected in Texas. The two evaluation programs can be synthesized into a single set of material selection guidelines.

CHAPTER 1. INTRODUCTION

1.1 PROBLEM STATEMENT

Structural concrete repairs are growing in importance as a result of the aging of the nation's infrastructure. Properly executed repairs will allow these structures to continue to fulfill their purpose by extending their service lives.

The repair process follows three basic steps: diagnosing the cause of the problem, developing required performance criteria, and choosing the most appropriate repair material. It is this last step — material selection — that is often the most difficult. Currently no accepted standards exist that can be used as a guide in the selection of a material. There is some guidance provided by manufacturers' publications and from organizations such as the International Concrete Repair Institute (ICRI), but there are no universally accepted specifications. Another problem is that there are no standard material property tests that must be reported by the manufacturers that allow comparisons to be made between the different materials. To an inexperienced engineer, the selection process can be overwhelming, owing to the number of products currently available.

Part of the difficulty in establishing national specifications has been the shear complexity of the problem. For example, it has been determined that each repair must be independently evaluated in order to take into account all the applicable variables. As a result, the current selection of a repair material is based primarily upon a trial-and-error process.

1.2 OBJECTIVE OF RESEARCH PROGRAM

The primary objective of this research project was to obtain data that can be used to develop guidelines that will aid engineers in the selection of the most appropriate concrete repair material. The information and data were gathered from two sources: a laboratory evaluation program and a field evaluation program. In the laboratory evaluation program, the most important material properties corresponding to a successful repair were identified and the appropriate tests were chosen to best represent these properties. The field evaluation program was used to evaluate the performance of existing repairs that were subjected to different climatic conditions. Information obtained from the two evaluation programs was then synthesized.

1.3 SCOPE

This report has three main parts. The first part, comprised of Chapters 2, 3, and 4, describes the material selection process. Chapter 2 presents pertinent background information about techniques currently being used to evaluate repair conditions. In addition, the chapter describes the creation of material performance criteria for a repair, along with recent significant research in the area of concrete repair. Chapter 3 describes the generic types of repair materials available and their typical property values. Chapter 4 then describes the testing procedures followed in this study; this includes all the basic properties identified as being essential for a successful repair.

The second part of this report, comprised of Chapters 5 and 6, presents the results obtained from the laboratory and field evaluation programs. The third part, Chapter 7, the final chapter of the report, discusses conclusions and recommendations obtained from the synthesis of the laboratory and field results.

CHAPTER 2. BACKGROUND

2.1 INTRODUCTION

The purpose of this chapter is to identify and discuss the factors that need to be considered during the repair material selection process. This requires a systematic evaluation of all pertinent information. For most repairs, more than one material will perform satisfactorily; consequently, other criteria, such as economics, available skill, and equipment, need to be evaluated.

One of the first steps in the selection process is to develop performance criteria for the repair material. The performance criteria should consist of minimum threshold values for the various material properties that are essential in a successful repair. Unfortunately, few attempts have been made to establish standardized industrywide specifications for the repair material selection process, and even fewer attempts have been made to quantify the selection process by specifying minimum property values. Even though material selection process documents are helpful in ensuring that all pertinent repair conditions are considered, the process can still be a matter of trial and error unless adequate property values of the materials are available. The current trend is moving toward more quantified performance criteria and more guidance.

2.2 TYPES OF CONCRETE DISTRESS

There are many mechanisms that may cause damage to the concrete elements of a bridge or other concrete structures. In some cases a combination of problems may have led to the concrete failure; in any event, determining the cause or causes can be difficult, if not impossible. For most commonly encountered repairs, the type of substrate failure can be categorized into one of the following broad groups (Ref 1):

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

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

(3) *Defective Concrete:* Concrete that needs to be repaired because problems have evolved as a result of faulty design, construction, or materials (i.e., alkali-aggregate reaction).

The purpose of a repair is to successfully return the damaged section back to its intended function. While there are different methodologies used in the repair process, the following is a list of typical steps taken.

(1) Evaluation of the cause of substrate failure

(2) Removal of all damaged concrete and, if possible, the cause of the problem

(3) Cleaning and/or replacement of damaged or corroded reinforcing

(4) Development of a material performance criteria based on repair demands
(5) Selection of a material with properties most closely matching those derived from step 3
(6) Application of the repair material

The first two steps are routinely done without major problems. The difficulty comes in trying to complete steps 4 and 5. The following section describes the currently accepted methods used to fulfill these steps.

2.3 DEVELOPING PERFORMANCE CRITERIA

There are three main considerations when developing a performance criteria and selecting a repair material: (1) evaluating the repair conditions; (2) determining the material properties; and (3) selecting a material. The evaluation of repair conditions is discussed in this chapter, while the latter two steps are explored in depth in the following chapters. The flowchart in Figure 2.1 illustrates the process that needs to be followed in order to create performance criteria for a repair. Figure 2.1 subdivides the condition evaluation process into four main areas:

- Application Conditions
- Strength Requirements
- Curing/Special Considerations
- Durability

By obtaining the background information presented in the flow chart (along with any information that is unique to the particular repair situation), it is possible to identify the pertinent material properties dictated by the repair conditions. The last step shown in the flowchart is to develop the performance criteria for the repair by specifying minimum property values that the material must possess in order to qualify as a possible material candidate. The property values should be based upon laboratory tests and, when possible, from actual field performance that corresponds to successful repair involving similar conditions.

While in theory developing performance criteria appears straightforward, in actuality the process is extremely complicated. The two primary reasons for the difficulty are (1) insufficient data from laboratory tests that can be used to establish the minimum property values, and (2) lack of property values for all the proprietary products. As a result the major dilemma in developing performance criteria is determining the minimum material property values that need to be met after the repair conditions have been evaluated. For example, what coefficient of thermal expansion should the repair material have if it is subjected to a large number of thermal cycles? The problem with specifying a particular material property value is that little research has been done to establish the level of stress or fatigue at which the patch will fail; also unknown is how much of a difference in coefficient of thermal expansion between materials will cause this failure to occur. Most of these difficult questions are currently answered through experience. Normally, a trial-and-error process precedes the establishment of a rule of thumb.

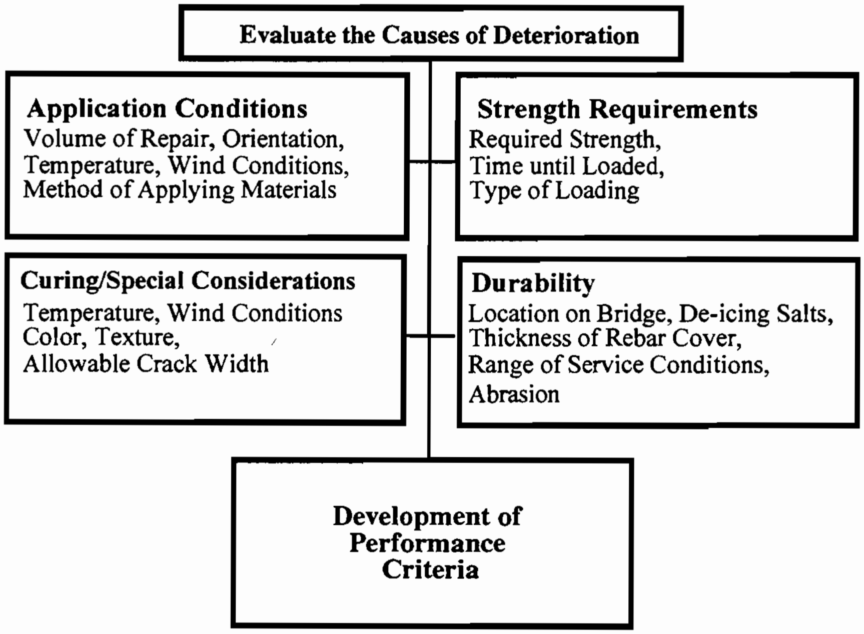


Figure 2.1 Development of performance criteria

The forerunners in developing performance criteria for repair materials have been state transportation departments. The direction typically taken by these agencies is to establish standardized tests that a material must pass in order to be placed on an approved list of repair materials. There are usually different approved lists depending upon the type of application (overhead, vertical, or horizontal) and whether it is a rapid-setting material or not. The problem with pre-approved lists is that a material may be randomly chosen without properly matching the repair demands to the material properties. The use of an approved list of materials may be the cause of premature concrete repair failures if it is used without consideration of other factors.

Recently, there have been advances in developing guidelines that may be used for building performance criteria. Two such sources are "Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces," published by the International Concrete Repair Institute (ICRI) (Ref 2), and the previous report from this project (Ref 1). Both documents, developed independently, follow the same basic format of:

(1) identifying all the important material properties that need to be considered to ensure a successful repair (building performance criteria);

(2) recommending test methods that may be used to obtain the desired material property values; and

(3) providing guidance in selecting a repair material that possesses the desired properties.

The first step recommended from both sources is to complete a condition evaluation sheet. The form ensures the evaluation of all pertinent information about the repair.

One of the primary objectives of this report is to validate the procedure recommended in the first report. The information in the first report is based solely on a thorough literature review of the repair field. Using both laboratory and field tests, the proposed repair methodology and property values from the first report were evaluated.

2.4 SIGNIFICANT RESEARCH

Much of the recent research into repair materials has been focused on linking laboratory property values to the actual field performance of the repair materials. For these studies, repair locations were carefully chosen in order to select different repair conditions and to expose the repairs to specific environmental conditions. These studies have had limited success in correlating the laboratory and field results. The main difficulty has been caused by the service lives of the repairs outlasting the length of the research projects. An example of a project that is tracing the performance of patches placed in various climatic regions is a study by the Strategic Highway Research Program (SHRP-89-H-106) (Ref 3). This study is measuring physical properties tested in the laboratory, and is evaluating how the repairs are performing after 10 months. From the results, an attempt was made to statistically correlate the data with performance. Unfortunately, too much scatter in the data prevented a correlation from being established. A similar project, the "Alberta Concrete Patch Evaluation Program" (Ref 4), led to conclusions similar to those found in the SHRP project. The Alberta project found that the rankings of the materials according to physical properties determined in the laboratory program did not correlate well with the field performance.

An ongoing project being conducted by the U.S. Army Corps of Engineers, dubbed "Performance Criteria for Concrete Repair Materials, Phase 1" (Ref 5), is similar to the previously discussed projects, except that its primary focus is on specifically trying to correlate repair performance with compatibility with the substrate. The project is still in the preliminary stages, and no data have yet been collected. The difference between this project and the other studies is that an intensive investigation into testing the compatibility properties was made. For example, this project has narrowed the number of material properties that are being evaluated as having a possible correlation to a successful repair. The properties considered in this study are compressive strength, tensile strength, modulus of elasticity, creep, coefficient of thermal expansion, and shrinkage. These are the properties that are being used to determine a repair material's dimensional compatibility with the substrate.

CHAPTER 3. MATERIAL SELECTION

3.1 CLASSIFICATION OF MATERIALS

The first step in selecting materials for use in this project was developing a classification scheme. There are many different ways in which materials may be classified. The difficulty with many of the classifications is that manufacturers often do not reveal all the constituents of the prepackaged repair materials. For this project, the repair materials were classified according to the type of primary binder that is present. Table 3.1 shows the five material categories that were created in order to classify all the types of repair materials most commonly used in the field to make structural repairs.

3.2 PHYSICAL PROPERTIES OF REPAIR MATERIALS

There are many variables that need to be considered when choosing an appropriate repair material. When considering the unique conditions of each repair, it becomes obvious that a wide variety of products are available from manufacturers. A particular product typically is chosen for one or more desired properties necessary to match the repair conditions, without regard to any disadvantages associated with the material. For example, an epoxy might be used when low permeability or excellent bond is required, but the mismatch in coefficient of thermal expansion which might cause debonding to occur is not considered.

Table 3.1 Material categories

CATEGORY	BINDER TYPE
I	Portland Cement Concrete (PCC)
II	Magnesium Phosphate Concrete (MPC)
III	Epoxy Polymer Concrete (Epoxy PC)
IV	Methyl Methacrylate Polymer Concrete (MMA PC)
V	Latex-Modified Concrete (LMC)

Typical property values for repair materials can vary substantially, even within the same material category. Tables 3.2 and 3.3 show some typical properties for different types of repair materials from two separate sources. It is interesting to compare properties in this way to see the strengths and weaknesses of each material. For example, resin mortar has 2 to 3 times the compressive and tensile strengths of PCC, but the coefficient of thermal expansion is also increased by approximately the same magnitude. From the tables it is obvious that selecting a repair material requires compromise between the desired material properties.

Table 3.2 Typical substrate and repair material property values (Ref 5)

	MATERIAL CATEGORY		
Property	Plain Cementitious Mortar	Polymer-Modified Cementitious Mortar	Resin Mortar
Compressive Strength (MPa)	20-50	30-60	50-100
Tensile Strength (MPa)	2-5	5-10	10-15
Modulus of Elasticity (10^4 MPa)	2-3	1.5-2.5	1-2
Coefficient of Thermal Expansion (10^{-6}/°C)	10	10-20	25-30
Water Absorption (% by mass)	5-15	0.1-0.5	1-2

Table 3.3 Typical repair material property values (Ref 2)

	MATERIAL CATEGORY					
Property	PCC	Latex-Modified		Magnesium Phosphate Concrete	Epoxy Polymer Concrete	MMA Polymer Concrete
		Neat	Extended			
Compressive Strength (MPa)	35	25	40	60	85	85
Modulus of Elasticity (x10^4 MPa)	2.6	1.7	1.7	2.2	1.1	1.4
Drying Shrinkage*	Moderate	Moderate	Low	Low	Low	Moderate

*Drying Shrinkage: Very Low <0.025%
Low 0.025% - 0.05%
Moderate 0.05% - 0.1%
High >0.1%

Because many factors have an effect upon property values, Tables 3.2 and 3.3 represent only approximate values within each material property category. Property values differ for each material type because of the type and amount of aggregate added to the mix. Most prepackaged repair materials recommend adding aggregate to repairs over 10-mm deep. In most situations, aggregate can improve the material properties by decreasing shrinkage, improving durability, and decreasing coefficient of thermal expansion. Other reasons for the material properties to vary within the same category are the quantity of binder present and the types of fillers and additives added to the mix.

3.3 PROPRIETARY PRODUCTS

The actual proprietary material selection came from information gathered by surveys of TxDOT district offices (Ref 1) and through an investigation into frequently used materials. Overall this led to the selection of nine different materials for testing (Table 3.4). At least one material was chosen for each of the five material categories discussed previously. In addition, four more materials were chosen because they were found to be extensively used in the repair of structural concrete. For example, three materials were evaluated in the PCC category after our investigation revealed that they were all frequently used in the field. Even though they are all classified within the same category, each material possesses different characteristics and is recommended for different types of applications. The materials chosen are representative of those currently available and frequently used in the field.

Table 3.4 Proprietary materials

CATEGORY	GENERIC NAME	PROPRIETARY NAME	MANUFACTURER
PCC	PCC 1	Duracal	U.S. Gypsum Company
	PCC 2	TxDOT Class "K"	N/A
	PCC 3	Emaco S88-CA	Master Builders
MPC	MPC 1	Set 45 Hot Weather	Master Builders
Epoxy PC	Epoxy PC 1	TxDOT Type VIII	Industrial Coatings
	Epoxy PC 2	BurkEpoxy Mortar	Burke
MMA PC	MMA PC 1	T 17 Polymer Concrete	Transpo
LMC	LMC 1	SikaTop 122	Sika
	LMC 2	Burke-Krete Overlay / Repair Mortar and SBR	Burke

As previously discussed, a difficulty in selecting a repair material is the lack of standard material property tests that can be used for comparison purposes. The technical data sheets supplied by the manufacturers often do not provide sufficient information necessary to make a sound engineering decision on which material to choose for a particular repair. The main problems associated with technical data sheets are: different manufacturers often use a variety of test methods to evaluate the same material property; the test procedures are modified without explanation; the test method followed is not reported; or the property values are not given. An example of an important property not always reported by manufacturers is shrinkage. Even though it is one of the most important properties for any repair, finding accurate information can be quite difficult. Table 3.5 shows the range of material property test methods reported by various manufacturers on their technical data sheets for the repair materials being used for this study.

Table 3.6, which summarizes the material property values reported by the manufacturers, demonstrates the range of values that can be expected by the repair materials being evaluated in this project. Even when an attempt is made to organize all available information into a table, a comparison between products can still be very difficult.

Table 3.5 Reported material tests of the proprietary products

	PCC			MPC	Epoxy PC		MMA PC	LMC	
Property	Duracal	Class "K"	Emaco	Set 45	Type VIII	BurkEpoxy	T17	Sika 122	Burke-Krete
Compressive Strength			ASTM C109	ASTM C109*		ASTM C579	ASTM C109	ASTM C39 ASTM C109	ASTM C109
Flexural Strength			ASTM C348	ASTM C348		ASTM C580	ASTM C348	ASTM C78	
Modulus of Elasticity			PROVIDED	ASTM C469			PROVIDED		
Plastic Shrinkage							DuPont		
Drying Shrinkage				ASTM C157*		ASTM C531			
Coefficient of Thermal Expansion				CRD-C39		ASTM C531	ASTM C531		
Bond			MB METHOD				ACI 503R	ASTM C882*	
Splitting Tensile			ASTM C882	ASTM C882*				ASTM C496	
Tensile						ASTM C307	ASTM D638		ASTM C190
Absorption									
Abrasion							ASTM C501		
Permeability			AASHTO T-277						
Freeze/ Thaw			ASTM C666-A	ASTM C666*			ASTM C666		
Chemical Resistance			ASTM C1012	ASTM C672 ASTM C1012					
Working Time									
Set Time				ASTM C266					

* Modified test

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	

3.4 MATERIAL PREPARATION

Each material was mixed and cured according to the manufacturer's recommendations. When applicable, the materials were mixed and tested using both a neat and fully extended mix with 10-mm pea gravel and/or sand having a fineness modulus of 1.63. By testing both the neat and extended mixes, a range of the material properties was established. The following sections describe the repair materials evaluated in this study.

3.5 PORTLAND CEMENT CONCRETE

The most commonly used binder present in repair materials is portland cement. Typical mixes include a mixture of cement, water, coarse aggregate, sand, and a variety of additives. If it is a prepackaged material, it is usually a one-component system, where the required quantity of water is added to 18 to 22 kg of dry powder. The major advantage of using a PCC mix is that it has properties similar to those of the substrate and, as a result, many of the compatibility problems associated with the other types of materials are eliminated. Other reasons why cementitious repair products are widely used are that they are economical, easy to use, and can have their properties significantly enhanced through additives. Table 3.7 provides examples of different types of modifiers and the corresponding property that is enhanced. Polymer latexes are commonly added to PCC mixes and, owing to their abundant use, they are classified as polymer-modified concrete.

Table 3.7 Possible modifiers for portland cement-based materials (Ref 1)

Classification	Type	Properties Affected Positively
Polymer Modifiers	Polymer Latexes	Bond, Durability
Other Cements	High Alumina Cements Gypsum	Setting Time, Strength Setting Time, Strength
Chemical Admixtures	Accelerators Water Reducers Super Plasticizers	Setting Time, Strength Gain Workability, Strength, Durability Workability, Strength, Durability
Mineral Admixtures	Pozzolans (i.e., Fly Ash) Slags (i.e., Silica Fume)	Workability, Strength, Durability Workability, Strength, Durability
Air Entraining Agents	Air Entraining Agents	Workability, Durability
Misc. Admixtures	Expansive Agents Corrosion Inhibitors	Shrinkage Durability
Other Additives	Fibers	Durability, Non-Sag

One problem with PCC materials is their tendency to shrink. This can lead to cracking and durability problems, unless adequately controlled. Another disadvantage is that PCC often has property values lower than those associated with other types of materials. The three different proprietary PCC products evaluated in this study are discussed below.

3.5.1 Duracal

Duracal is a rapid-setting cementitious material that expands upon setting. It is a one-component system, to which water is added, that can be extended with sand and coarse aggregate and that is recommended for use in horizontal applications that are subjected to loads (i.e., traffic). It does not require moist curing.

3.5.2 TxDOT CLASS "K"

TxDOT Class "K" is a full-depth repair material typically used on bridges. It is described in TxDOT specifications as a seven-sack (305 kg) Type III cement mix. The mix requires a water content of 20.8 L or less per sack of cement, as well as a water reducer and a set-accelerator. The only strength requirement is that it must achieve a minimum flexural strength of 2.93 MPa within 24 hours. The actual mix proportions are given in CTR Report 311-3, "Evaluation of Accelerated Concrete as a Rapid Setting Highway Repair Material" (Ref 6), and were determined from trial mixes.

3.5.3 EMACO S88-CA

Emaco S88-CA is a modified cementitious material that contains silica fume, fiber reinforcement, and shrinkage-compensators. It is a one-component mortar system that can be used for horizontal, vertical, and overhead applications. Proper curing is required, by either continuous moist cure for seven days or by applying a curing compound. It is not recommended to be extended with sand or aggregate.

3.6 MAGNESIUM PHOSPHATE CONCRETE

Magnesium phosphate materials have also been used successfully in the repair of concrete structures. Commonly available products usually come in a one-component system activated by the addition of water. It is recommended that they be extended with aggregate for thicker placements. Some advantages are having a similar coefficient of thermal expansion as PCC and the ability to develop a strong bond to a dry substrate. It also has a rapid strength gain and low drying shrinkage properties. Some problems associated with this material are loss of strength, if too much or too little water is used, and internal microcracking during mass pours, owing to the substantial heat generated during the hydration process (Ref 1).

The magnesium phosphate concrete material evaluated in this project was Set 45 Hot Weather. It is a rapid-setting one-component repair material specifically formulated for hot weather conditions. It should be used for horizontal applications and can be extended for patches greater than 25 mm in depth. The mix is highly sensitive to water content, and dramatic losses of strength can occur if more water than required is added. Precaution must be taken to use non-calcareous aggregate to avoid an undesirable reaction. It does not require moist curing or use of a curing compound.

3.7 EPOXY POLYMER CONCRETE

Epoxy materials, when used under the proper conditions, exhibit extraordinary material properties. They have high compressive and flexural strengths, rapid strength gain, bond well to substrates, exhibit great durability properties, and have low shrinkage. They are very cohesive and can be applied to vertical and overhead applications. Yet despite all their benefits, there are many instances when they may not be the best material selection. One major drawback is that they are expensive. If a cementitious repair material can perform adequately, then there may be no reason to use an epoxy. As a result of epoxy's physical properties being much different than cementitious materials, a major area of concern is incompatibility, which can lead to a premature failure. It is possible to extend the mix with aggregate and lower the coefficient of thermal expansion, but some incompatibility will still exist. Figure 3.1 illustrates the effect aggregate has on an epoxy's coefficient of thermal expansion. While it is theoretically possible to decrease the coefficient of thermal expansion to a value similar to that of the substrate, this may not correspond to the optimal mix proportions. The amount of polymer needs to be sufficient to coat all the aggregate and maintain the desired strength and durability.

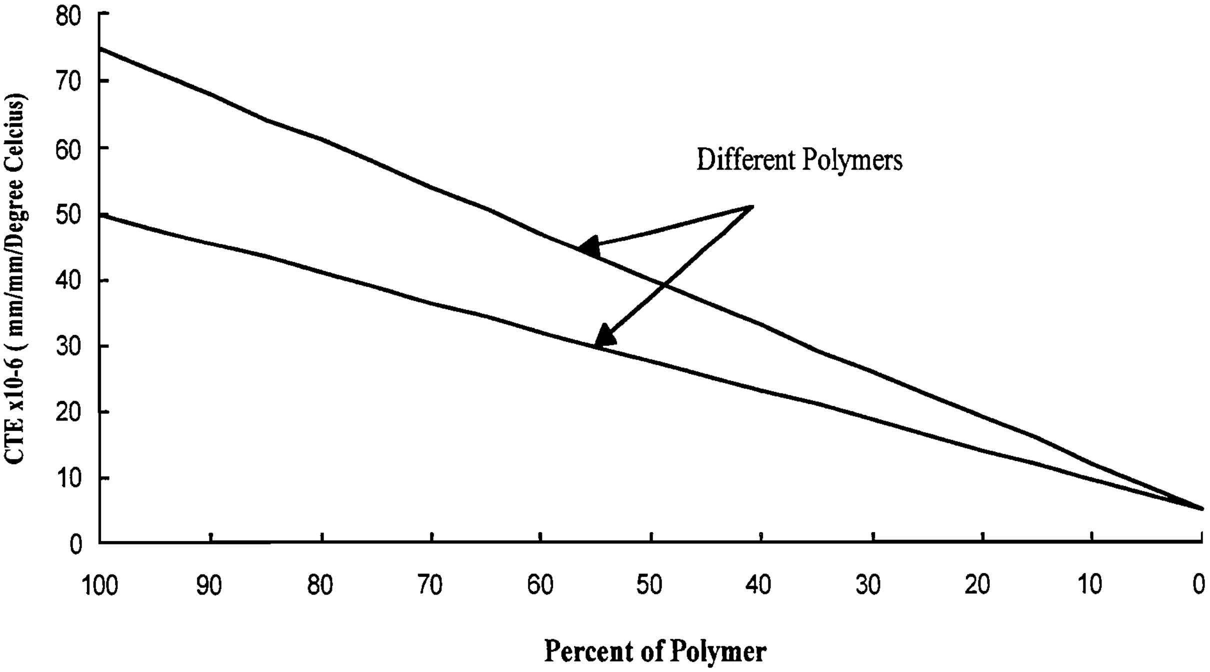


Figure 3.1 Effect aggregate has on polymer materials

Typically, epoxies come in two-component systems, consisting of a resin and a hardener. Sand or coarse aggregate, depending upon the thickness of the repair, is also normally added to the mix in varying amounts. The actual quantity of aggregates used depends on the repair conditions.

3.7.1 TxDOT Type VIII

Type VIII epoxy is a standard material that, according to TxDOT specifications, is used in "repairing spalls and other defects in existing portland cement concrete" (Ref 7). The extended mixes are not required to meet any strength or durability requirements as stated in the specifications. The material is used extensively in precast concrete plants to repair damaged structural members. It comes in a two-component system (resin and hardener), to which dry sand is added to produce a mortar.

3.7.2 BurkEpoxy Mortar

BurkEpoxy mortar is a prepackaged, three-component system that consists of resin, curing agent, and blended aggregates. It is a general purpose patching material that its manufacturer claims will repair spalls, large cracks, or serve as an underlayer. The manufacturer does not recommend extending the mix with aggregates beyond what is supplied.

3.8 METHYL METHACRYLATE CONCRETE

MMA polymer concrete typically exhibits rapid strength gain, high mechanical property values, and great durability properties. These materials are capable of bonding tenaciously to the substrate and require no special curing conditions. Some disadvantages are a low flash point, short working time, and a strong odor. High molecular weight methyacalate (HMWM), a relatively new material, performs similarly to MMA but has a longer working time and less odor. Typically, MMA comes in a two-component mortar system, to which coarse aggregate can be added for thicker repairs.

The MMA material evaluated in this study was Transpo T17. It is a two-component system consisting of an MMA liquid component and a powder component of various fillers. The manufacturer recommends extending the mix when the repair thickness exceeds 13 mm. The amount of extension increases in direct proportion to the repair thickness. The material has low viscosity and is meant to repair horizontal surfaces. It requires the use of a primer, and no special curing is necessary.

3.9 LATEX-MODIFIED CONCRETE

Latex-modified concrete, a specific type of polymer-modified concrete, is formed by the addition of latexes in the mixing water of hydraulic cement. The most common types of polymers added to hydraulic cements are styrene-butadiene rubber (SBR) and acrylic latex. Latex-modified materials may be purchased as a one-component system (re-dispersible polymer powder) or as a two-component system, where the latex comes already mixed with the water in disposable plastic bottles.

The material properties are enhanced by the presence of the polymer, but the cost is also increased, although not as much as for polymer concrete. Some advantages include promotion of a strong bond, increased tensile and compressive strengths, and a reduction in permeability. The disadvantages are cost increase and the need for moist curing, unlike polymer concretes.

3.9.1 SikaTop 122

SikaTop 122 is a two-component, polymer-modified repair material. It can be used for both horizontal and vertical surfaces. For repairs having a depth greater than 26 mm, it can be extended by up to 19 kg of coarse aggregate. The repair material should be applied to a saturated surface dry substrate. Proper curing techniques are required by maintaining a moist surface with wet burlap, fine mist, or a curing compound.

3.9.2 Burke-Krete Overlay/Repair Mortar and SBR

Burke-Krete is a two-component, cementitious-based material modified with SBR. The latex is dispersed with water in a plastic bottle and is added to the cement. It cannot be extended and is limited to applications of 13 mm. For deeper repairs, multiple lifts may be applied until the desired thickness is reached. It is typically used for horizontal repairs and for leveling purposes.

CHAPTER 4. LABORATORY EVALUATION PROGRAM

4.1 INTRODUCTION

In order to properly evaluate the various materials, it was first necessary to obtain their basic material property values. The properties most relevant for a successful repair were identified and then the appropriate test methods were chosen. To obtain an idea of which test methods are currently being used, an investigation into what the manufacturers most commonly used was conducted. It was found that for most properties, there was a wide range of tests currently being used by the various manufacturers. The final decision was then based on which test method best represented the material property under consideration.

4.2 TEST METHOD DESCRIPTIONS

Three different categories of material properties were evaluated in the testing program:

(1) Mechanical properties
(2) Compatibility properties
(3) Durability properties

The degree of importance of each category is dependent on the specifics of the repair. For example, the mechanical properties will be of less importance than the compatibility and durability properties when a repair is more aesthetic than structural. ASTM testing procedures were followed for all material testing, except for the shrinkage and bond tests. A summary of the material properties tested and the corresponding test method used is shown in Tables 4.1 to 4.3.

Table 4.1 Mechanical properties tests

MECHANICAL PROPERTIES		
PROPERTY		TEST METHOD
Compressive		ASTM C39
Flexural	(Neat)	ASTM C348
	(Extended)	ASTM C78

Table 4.2 Compatibility properties tests

COMPATIBILITY PROPERTIES	
PROPERTY	TEST METHOD
Modulus of Elasticity	ASTM C469
Shrinkage	DuPont
Coefficient of Thermal Expansion	ASTM C531
Bond	ACI-503R Modified

Table 4.3 Durability properties tests

DURABILITY PROPERTIES	
PROPERTY	TEST METHOD
Absorption	ASTM C413
Abrasion	ASTM C418
Permeability	ASTM C1202

4.3 MECHANICAL PROPERTIES

The most commonly used technique to assess the quality of concrete is to evaluate its mechanical properties (i.e., its compressive and flexural strengths). A repair material's compressive and flexural strengths may or may not be of significant importance, depending on the specifics of the repair. The mechanical properties are most important when the repair will be required to carry or transfer load or to resist internal stresses developed as a result of differences in volume change between the repair material and substrate concrete.

4.3.1 Compressive Strength

ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," was used to determine the strengths of the neat and extended mixes, using 76-mm x 152-mm cylinders. Unbonded neoprene pads were used in lieu of the conventional sulfur mortar caps. The specimens were loaded at a uniform rate of 0.30 MPa/second. The tests were conducted on three companion specimens at 1, 7, and 28 days.

4.3.2 Flexural Strength

The flexural strengths for the neat mixes were determined using ASTM C348, "Standard Test Method for Flexural Strength of Hydraulic Cement Mortars," with 25-mm x 25-mm x 305-mm specimens. ASTM C78, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)," was used to determine the strengths of the extended mixes using 76-mm x 76-mm x 305-mm specimens. The specimens were centered on supports 229 cm apart and then loaded by either center-point or third-point loading, depending on the test method. The specimens were loaded at a uniform rate of 0.60 mm/minute until failure occurred. The tests were conducted on three companion specimens at 1, 7, and 28 days.

4.4 COMPATIBILITY PROPERTIES

The compatibility between the repair material and substrate concrete is of vital importance in a successful repair. Compatibility can be defined as "the balance of physical, chemical and electro chemical properties and dimensions between the repair phase and the existing substrate phase of a repair system" (Ref 8). Yet even given this definition, many different interpretations can be made of what is meant by "compatibility." Deciding if a repair material should be labeled as compatible with a substrate depends on its material property values and on the service conditions it will be subjected to during its lifetime.

For most repair conditions, both the physical and chemical properties need to be considered when establishing a material's compatibility. Most chemical incompatibility can be avoided if the proper time is taken to evaluate how the two materials will react with one another and whether the type of repair material selected is consistent with the type of concrete distress. For example, using a repair material with a low pH level with a substrate that contains a high pH level should be avoided. The mismatch between materials will cause a reaction to occur, resulting in a poor bond between the materials. Another type of chemical incompatibility exists if an impermeable material is used for the repair of a permeable substrate. The repaired region becomes disassociated from the rest of the section and causes the corrosion to become isolated within one area. The presence of the repair material can actually be harmful because it expedites the corrosion process. Research has shown that the re-corrosion process occurs at a faster rate in a material that has uneven porosity. A test was performed where a steel bar was embedded into a material with uneven porosity. The corrosion process was monitored in both regions. The test revealed that the steel corrosion reaction is accelerated in the region of the lower porosity material, as compared with the region of the higher porosity material (Ref 9).

The physical compatibility of a material is also very important in achieving a successful repair. Whether or not a mismatch in these properties will cause a deterioration of the patch is dependent on the environmental and loading conditions that the repair will be subjected to during its lifetime. A common type of compatibility problem is caused by a difference in coefficient of thermal expansion between the repair and substrate materials if the repair is subjected to large temperature changes. Internal stresses will develop within each material as a result of the two materials attempting to move relative to one another when subjected to a temperature fluctuation. The same type of detrimental stresses are developed if the repair material chosen has high shrinkage. In this case, the internal stresses are due to the substrate achieving dimensional stability while the fresh repair material is still undergoing shrinkage. This is the reason why selecting a repair material with low shrinkage is highly desirable, if not mandatory. Incompatibility problems will also occur if there is a mismatch in the modulus of elasticity or creep between the repair and substrate materials. The problems associated with these properties are most noticeable when the repair is subjected to large loads or temperature changes. An example of a mismatch in modulus of elasticity is when the repair material is stiffer than the substrate. This can lead to the repair material failing first because it will attract a relatively larger portion of the load. Another problem is if the repair material has a larger creep factor than the substrate and deforms a differential amount when subjected to a sustained load. This can lead to the load being redistributed to the substrate over time.

To better understand the importance of compatibility, it is possible to represent a repair system using a three-part model, consisting of the substrate material, the interface, and the repair material (Ref 5). In order to achieve a successful repair, it is necessary for all three of these elements to act together as a system.

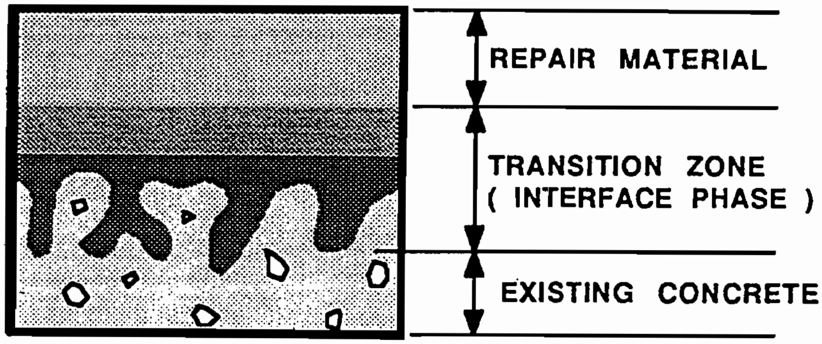


Figure 4.1 Idealized three-part model (Ref 5)

A failure in the system will occur if any one of its three parts fail. The more the three individual parts work together as a system, the more successful the repair. The three-part model visually illustrates how the overall performance of a repair will only be as strong as its weakest link. From Figure 4.1 it becomes evident that it is important to judge a repair material by more than just its mechanical properties. A repair material might have a high compressive strength, 41 MPa to 55 MPa, but be undesirable owing to a low bond strength. The system will never be able to take advantage of the repair material's high strength because the load is never transferred through the weak bond.

One of the consequences of not using a repair material that is compatible with the substrate is the generation of internal stresses caused by the differences in material properties. It was a primary goal of this project to identify the important compatibility properties and to test these properties. The compatibility properties tested are shown in Figure 4.2. Each property shown plays a role in how well the system will perform and must be considered during the material selection process.

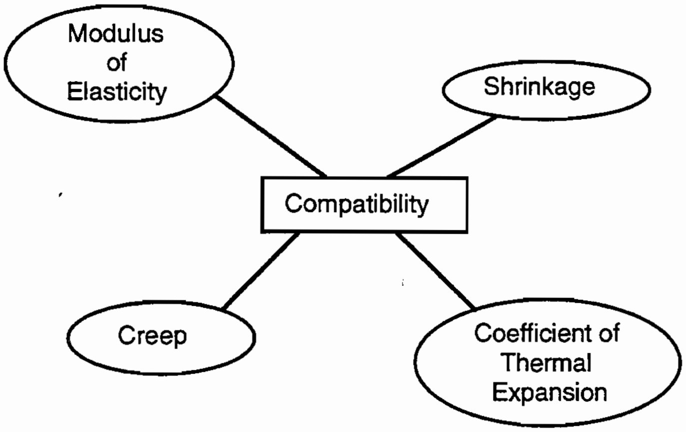


Figure 4.2 Compatibility properties

A general guideline in selecting repair materials is to choose a material that has properties similar to those of the substrate. Theoretically, if all the properties of the repair material are the same as the substrate properties, then the system would be perfectly compatible. Unfortunately, this is not always possible and many other variables need to be considered.

The acceptable level of property differences is dependent upon the type of repair material and the service conditions that it will encounter. For most repairs, as long as the bond strength is not significantly weakened by internal stresses and no durability problems arise from cracking, then the property differences are of little concern. Material property differences become of concern when high internal stresses develop. Internal stresses are generated when there is relative change in volume between the repair material and substrate that is restrained by the bond between them. The restrained change in volume is usually caused by shrinkage, differences in coefficient of thermal of expansion, and/or moisture change. A tensile failure will occur if the generated internal stresses become larger than any part of the system capacity (Figure 4.3). Depending upon the strengths of the materials, a tensile failure may occur in the repair material, at the interface, or in the substrate. The level of stress generated by expansion or contraction depends upon the modulus of elasticity of the material and how much the material can relax through creep.

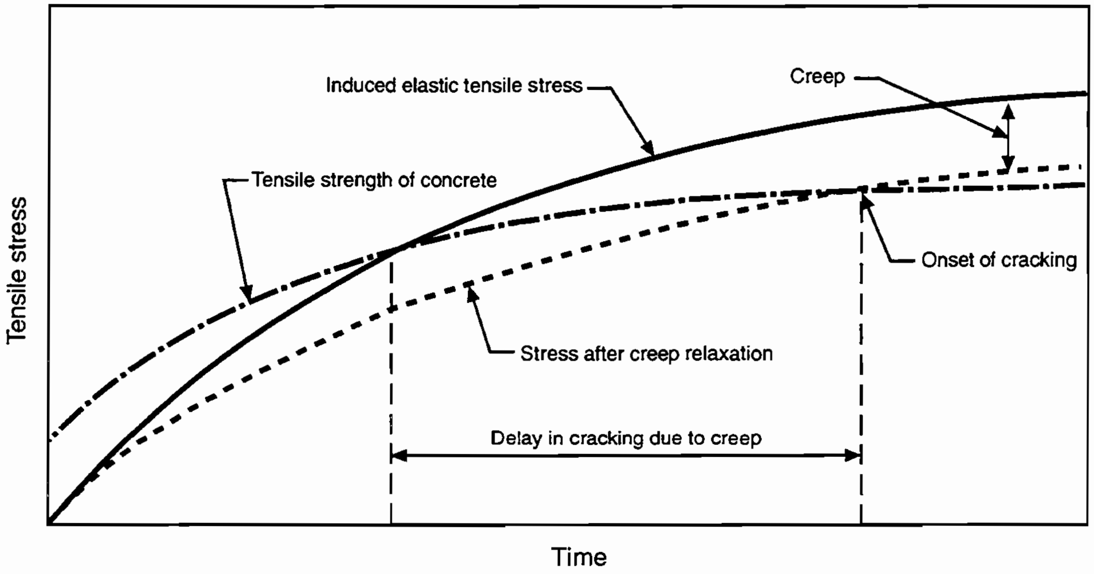


Figure 4.3 Internally generated cracking mechanism (Ref 5)

Accounting for both plastic and drying shrinkage in water-based cements can prevent repairs from cracking. Plastic shrinkage occurs in unhardened concrete, prior to setting, when the rate of evaporation exceeds the rate at which the bleed water reaches the surface. Often the loss of water from the top surface can be avoided if proper precautions are taken. Typical methods used to protect the fresh concrete from moisture loss include covering it with wet burlap or applying to it a curing compound. When the concrete reaches the hardened state, the volume change accompanying the loss of moisture is referred to as *drying shrinkage.* The shrinkage associated with resin-based materials occurs during the cooling period following the chemical reaction. For this project, both types of shrinkage were investigated. Early shrinkage was measured directly using the DuPont method (Ref 10), while the long-term shrinkage was evaluated indirectly in the bond test.

4.4.1 Modulus of Elasticity

The modulus of elasticity was determined using ASTM C469, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," with 76-mm x 15-mm cylinders. The procedure used to determine the modulus was to record the applied load when the deformation was 0.0153 mm and then to record the deformation when a load of 40 percent of the ultimate load was reached. The modulus is calculated as the $\frac{\Delta Stress}{\Delta Strain}$.

4.4.2 Shrinkage

The DuPont method was used to determine the plastic shrinkage of 76-mm x 76-mm x 305-mm specimens. When a material had both neat and extended mixes, only the neat was tested for shrinkage, owing to it being the worst case.

A non-stick liner was placed inside the mold prior to casting to reduce the friction and to allow the specimen to move more freely. Then the mold was filled with the repair material, and two angles were inserted into the specimen, one attached to a fixed plate, and the other angle attached to a plate that was allowed to move freely. As the material expanded or contracted, the relative longitudinal displacement between the two plates was monitored using a DCDT for a 24-hour interval. The amount of shrinkage was obtained by dividing the relative movement between the two angles by the initial gage length of 229 mm. The testing apparatus is shown in Figure 4.4.

4.4.3 Coefficient of Thermal Expansion

ASTM C531, "Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, and Monolithic Surfacings," was used to determine the coefficient of thermal expansion. The dimensions of the specimens were 25 mm x 25 mm x 30 mm for the neat mixes, and 77 mm x 77 mm x 30 mm for the extended mixes. For each material, the specimens were cast with a stud embedded in each end that was used to measure the lengths of the specimens. After allowing the specimens to cure a minimum of 28 days, they were measured using a length comparator at 22°C and then again at 100°C. The coefficient of thermal expansion was determined as the average length change of four specimens resulting from the temperature change.

4.4.4 Bond Strength

One of the most important properties for a repair material is its ability to bond with the substrate to form a composite material. While the importance of bond strength is known, there is no consensus as to the most desirable method to measure it. There are currently four methods in common use today (Ref 1): the slant shear bond test, direct shear bond test, direct tensile bond test, and flexural bond test. These four test methods are illustrated in Figure 4.5.

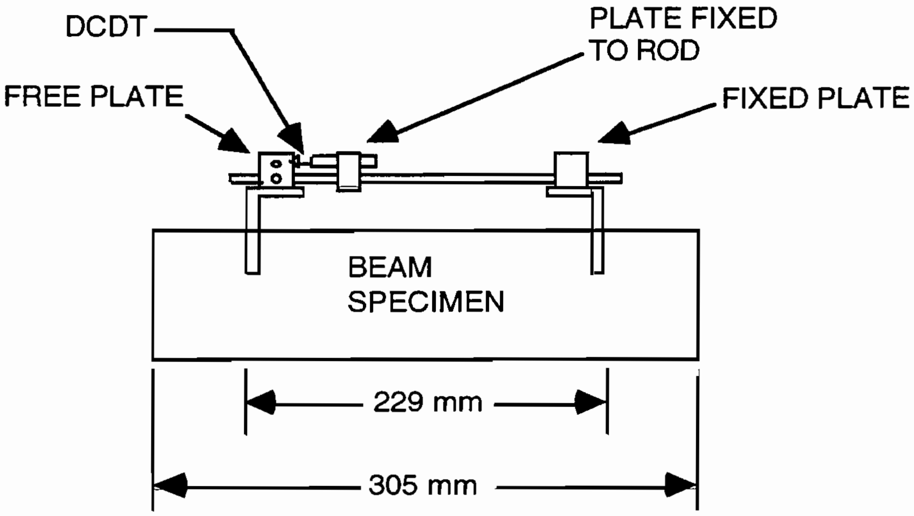
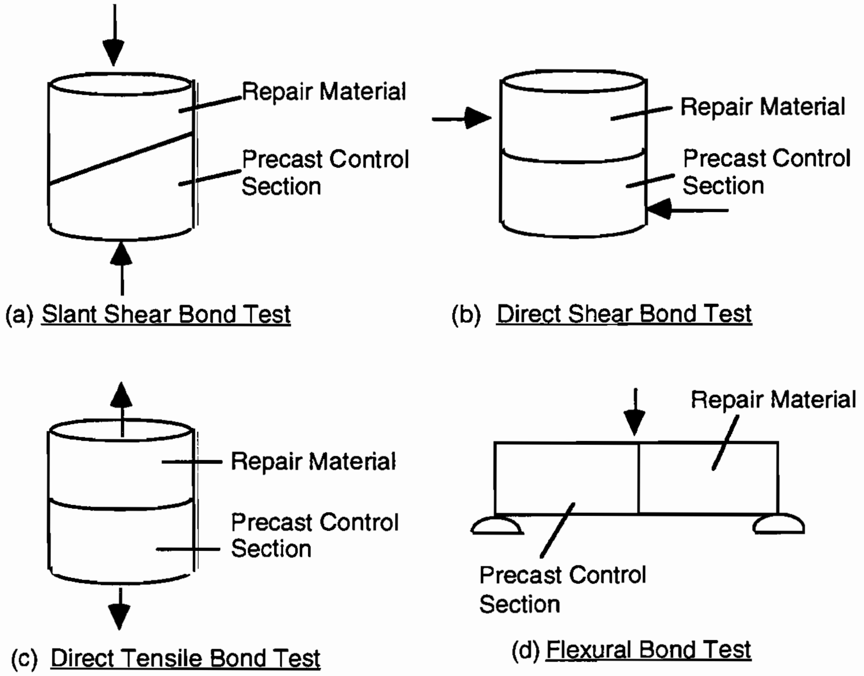


Figure 4.4 DuPont shrinkage test apparatus



(a) Slant Shear Bond Test

(b) Direct Shear Bond Test

(c) Direct Tensile Bond Test

(d) Flexural Bond Test

Figure 4.5 The four main types of bond tests

The testing of the bond strength in this study goes beyond determining the initial bond strength. It was also desirable to establish a correlation between a material's performance and its compatibility with the substrate. This was done by subjecting the specimens to thermal cycling and measuring the bond strength over time. The following section describes the test procedure used to evaluate the bond strength.

An adaptation of ACI-503R, "Direct Pull-Off Test" (Ref 11), was used to determine the bond strength. First, 30-mm x 30-mm x 89-mm concrete slabs were cast to act as the substrate. TxDOT Class "S" mix, commonly specified for bridges, was used. After allowing the base slabs to cure for at least 28 days, they were sandblasted 1 to 3 days before casting the repair material in order to obtain a rough surface. Molds were then placed around the specimens to the desired height, and the repair material was placed on the base slab (Figure 4.6). For each material, three different thicknesses were cast; the thickness depended upon the type of material and the recommendations made by the manufacturers. This led to a total of nine specimens being cast per material, with three specimens for each thickness. The thicknesses and type of mix (neat or extended) used for each type of material are shown in Table 4.4.

After casting, a curing compound was placed on the top exposed surface, if required, and the specimens were cured for seven days. After seven days they were cored, and the initial bond strength for each thickness was taken as the mean of three specimens.

Figure 4.6 Formwork used in casting repair materials

Table 4.4 Mix type and thickness of materials used for the bond test

	Bond Test (Mix Type and Thickness)			
	Repair Thickness			
Material	6 mm	19 mm	38 mm	76 mm
Duracal		Neat	Extended	Extended
TxDOT Class "K"		Extended	Extended	Extended
Emaco S88-CA		Neat	Neat	Neat
Set 45 HW		Neat	Extended	Extended
TxDOT Type VIII	Neat & Extended		Extended	Extended
BurkEpoxy Mortar	Extended		Extended	Extended
T17 Polymer Concrete	Neat	Extended	Extended	
SikaTop 122	Neat	Extended	Extended	
Burke-Krete Overlay/Repair Mortar and SBR	Neat	Neat	Neat	

The procedure used to obtain the bond strength consisted of coring the specimens with a 50-mm coring barrel approximately 6 mm beyond the interface of the repair material and substrate (Figure 4.7). Then, steel disks were secured on top of the core with epoxy. Using a Dyna pull-off tester, a tensile force was applied to the core until a failure occurred (Figure 4.8). Failure may occur in any of four different locations. These possible failure locations are in the substrate, at the interface, in the repair material, or in the epoxy (Figure 4.9). If the failure occurs in the epoxy, substrate or repair material, only a lower bound for the bond strength can be established.

Figure 4.7 Coring a laboratory bond specimen

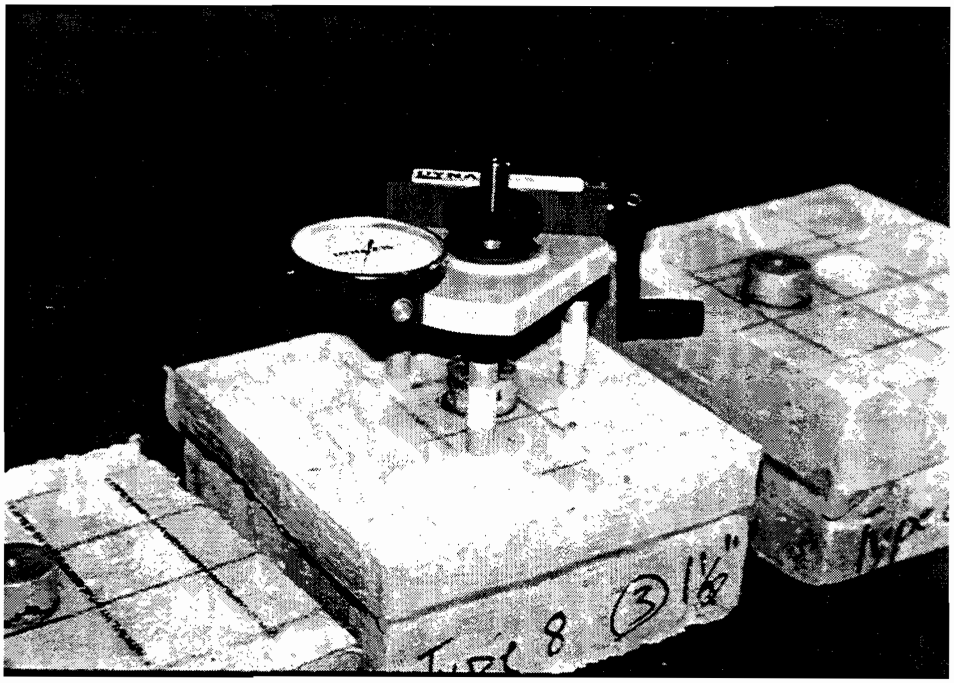


Figure 4.8 Equipment used for pull-off test

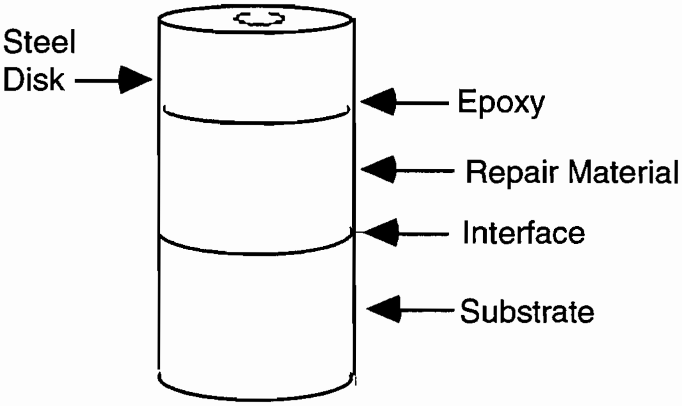


Figure 4.9 Failure modes of direct pull-off test

After obtaining the initial bond strengths, the specimens were placed into a chamber capable of thermal cycling (Figure 4.10). The specimens were then cycled four times a day, with alternating weeks of hot (10°C to 35°C) and cold (-12.2°C to 15.6°C) cycles (Figure 4.11). The temperature ranges were chosen to approximate the temperature cycles an actual repair in Texas may be subjected to during its lifetime. The two temperature ranges are induced to simulate winter and summer conditions. While not all repairs will be subjected to this type of thermal cycling, the ranges chosen represent a harsh environment that should provide a good test for the material.

The effect of thermal cycling on the bond strength was determined by conducting pull-off tests after the specimens had been subjected to a specific number of thermal cycles. This test was intended to determine the compatibility of each repair material with the substrate. A material was considered to be incompatible if the bond strength was weakened over time as a result of the thermal cycles. Even if the properties of the repair material differed from that of the substrate, as long as it is capable of withstanding the internally-generated stresses caused by the property differences, the material was considered successful. As a general rule, it was expected that the results would show that as the differences in material properties increased, the more incompatible a repair material would become with the substrate.

Figure 4.10 Environmental chamber used for thermal cycling

4.5 DURABILITY PROPERTIES

Durability is the ability of concrete to withstand chemical attack, abrasion, and other environmental conditions. One of the most commonly tested durability properties is permeability. Permeability is the ability of a material to transmit a fluid (liquids and vapors). One reason for concern over permeability is that corrosion of reinforcing steel is accelerated by a material having high permeability. A common solution for concrete that has failed by rebar corrosion is to use an impermeable material for the repair. Even though the cause of the problem is related to permeability, it may be more detrimental to use a repair material that is unable to transmit vapors and liquids. This is especially true when a repair material covers a large surface area, such as bridge deck overlays. The following describes the deterioration mechanism for impermeable materials:

> ...as temperatures drop, moisture in vapor form migrates towards the bond interface and converts to liquid at the dew point. Water solubles in the concrete are carried along with the migration. The liquid then turns to ice in freezing temperatures, resulting in freeze/thaw damage at the edge of the vapor barrier. (Ref 12)

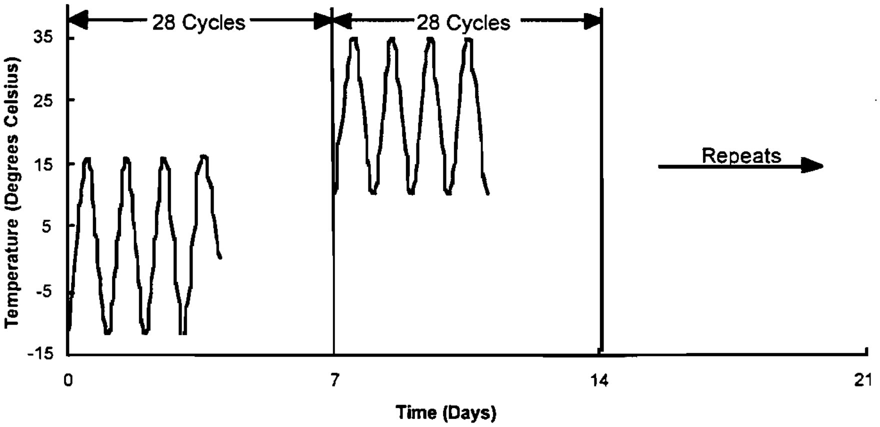


Figure 4.11 Temperature ranges for thermal cycles

Another way to measure the ability of a material to resist water penetration is by measuring its absorption. This property is important when a material will be subjected to large amounts of water. For concretes that are going to be subjected to wear from traffic, the concrete's resistance to abrasion is important. For many repair applications this is of little concern.

There are many ways to make a material more durable. For cementitious materials, the water-to-cement (w/c) ratio has long been regarded as directly related to many of the durability properties. As the w/c ratio decreases, there is less void space for water to occupy and cause damage to the concrete. Typical concrete damage that occurs as a result of a material having poor durability properties is corrosion of steel and freezing and thawing deterioration. Many of the durability problems become negligible when using polymer-based materials. Polymer materials can be used in locations characterized by harsh environmental conditions because they offer excellent protection for concrete that has been previously damaged.

4.5.1 Absorption

Water absorption was determined using ASTM C642, "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete." The specimens came from half the broken beams used for the flexural beam tests. The specimens were prepared by allowing them to cure for a minimum of 28 days and then cycled at 104°C until a constant weight was obtained. They were then submerged in water for at least 48 hours until two successive weighings at 24-hour intervals were the same. The percent absorption was calculated as the difference between the dry and saturated weights.

4.5.2 Abrasion

The abrasion resistance of the concrete specimens was tested using ASTM C418, "Standard Test Method for Abrasion Resistance of Concrete by Sandblasting." When applicable, both the neat and extended mixes were evaluated. The specimens came from the broken beams used in the flexural beam tests. The specimens were initially soaked in water for 24 hours prior to the test to achieve a saturated surface dry condition. The specimens were then placed 76-mm from an air nozzle and subjected to 0.41 MPa airflow that contained abrasive material (20-30 Ottowa sand). The test procedure consisted of sandblasting the specimens at eight different locations on their surfaces. Each spot was subjected to a sand flow rate of 600 g/min for a duration of 1 minute. In order to direct the airflow, a thin metal shield was placed over the specimen's surface that contained a 645-mm^2 circular opening. The resistance to abrasion is measured as the loss in weight determined as the difference in weights before and after the sandblasting. The test apparatus and setup are shown in Figure 4.12.

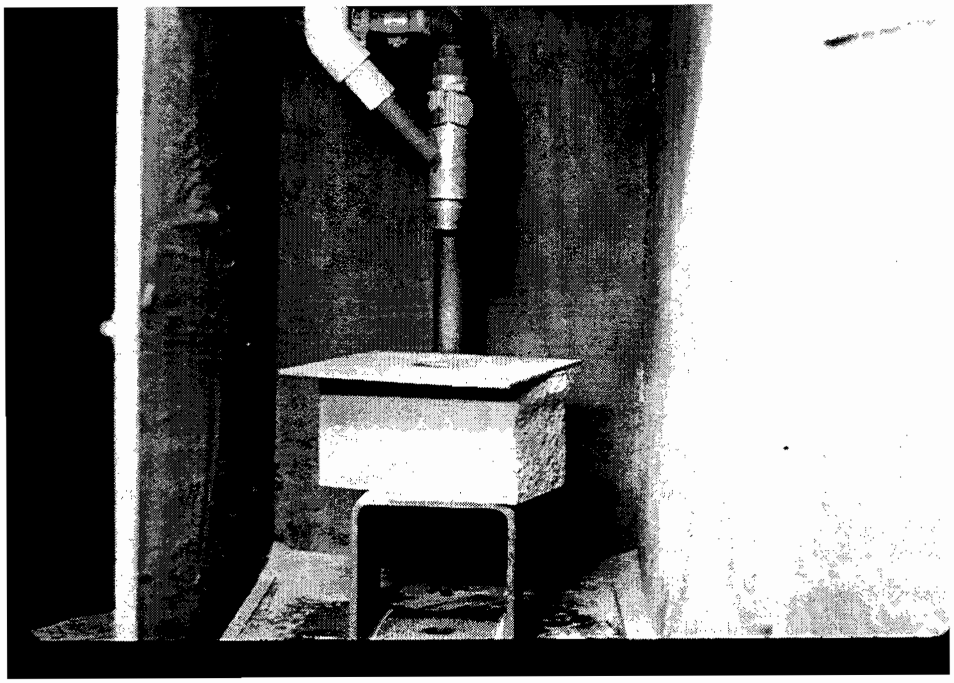


Figure 4.12 Abrasion testing apparatus

4.5.3 Permeability

ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," was used to determine permeability. Specimens consisted of two 50-mm slices cut from 76-mm x 152-mm cylinders. One side of the specimen was immersed in sodium chloride, the other in a sodium hydroxide solution. An indication of the permeability is found by measuring the amount of current that passed through the specimen over a six-hour span, while a 60 V potential difference was maintained between the specimen's two sides. The permeability was calculated as the area under the current versus time curve. The mean of two specimens was used to determine the permeability.

CHAPTER 5. LABORATORY EVALUATION PROGRAM RESULTS

5.1 INTRODUCTION

This four-part chapter presents the results of all the material property tests conducted for this project. The first three sections present the mechanical, durability, and compatibility property test results, while the last section summarizes the results and discusses the correlations between the property results and the bond strength. The results of each material property test are grouped either according to the five material categories established in Chapter 3, or with all the materials grouped together. Also the material properties of the typical substrate found in Texas bridges (TxDOT Class "S") are provided as a benchmark. The test results from both the neat and extended mixes are presented when applicable. The determining factor as to whether a neat, extended, or both mixes were used in this study was based on the manufacturer's recommendations.

5.2 MECHANICAL PROPERTY RESULTS

The two mechanical properties tested were the compressive and flexural strengths at 1, 7, and 28 days. The compressive strengths are presented in Figures 5.1 through 5.5, while the flexural strengths are shown in Figures 5.6 through 5.10. The cementitious-based materials performed extremely well in comparison with the other materials tested. The two highest 28-day compressive strengths were PCC 3 Neat and PCC 1 Neat. Both these materials can also be labeled as rapid setting materials because their 1-day strengths were well over 40 MPa. The polymer-based materials reached their ultimate strengths the quickest. It took only 1 day for the MMA and 7 days for the epoxies to obtain strengths that were extremely close to their 28-day strengths.

From the results obtained during the laboratory evaluation program, the compressive strength of the repair material should be of little concern during the selection process. This is because most of the materials tested obtained strengths that would be equal to or above that of typical substrate. As the use of high-strength concrete becomes more common it may be important in the future to consider the compressive strength of the repair material. For current typical concrete repairs, more effort should be spent evaluating other important repair material properties.

The polymer-based materials all had a much higher flexural strength than the other materials tested. This is especially true for the 1-day strengths, where their flexural strengths were 3 to 4 times larger than the other materials. For most of the PCC, MPC, and LMC materials tested, their 28-day flexural strengths were between 7 to 11 MPa, while the epoxies and MMA materials had strengths in the range of 19 to 22 MPa.

5.3 COMPATIBILITY PROPERTY RESULTS

The compatibility properties tested were the modulus of elasticity, coefficient of thermal expansion, shrinkage (Figures 5.11 through 5.17, Table 5.1) and the bond strength as a function of time.

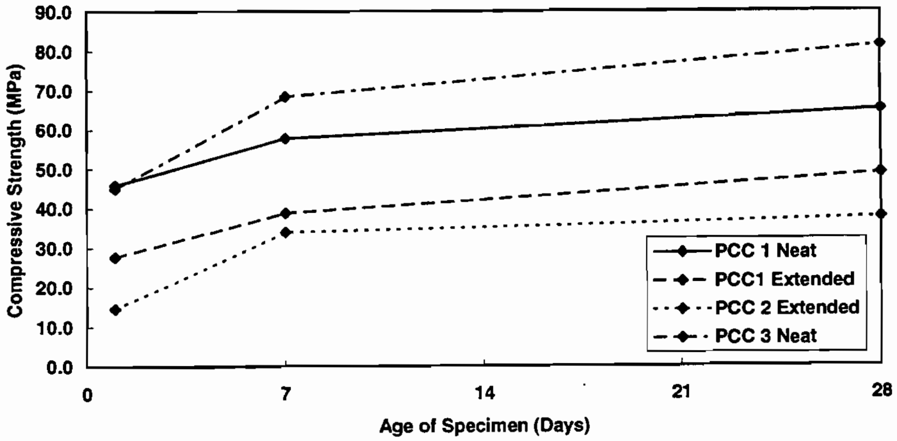


Figure 5.1 Compressive strengths of the portland cement concrete materials

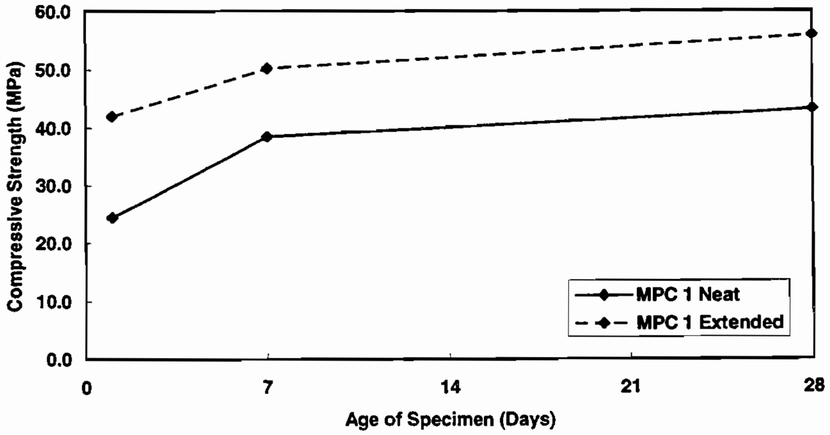


Figure 5.2 Compressive strengths of the magnesium phosphate concrete materials

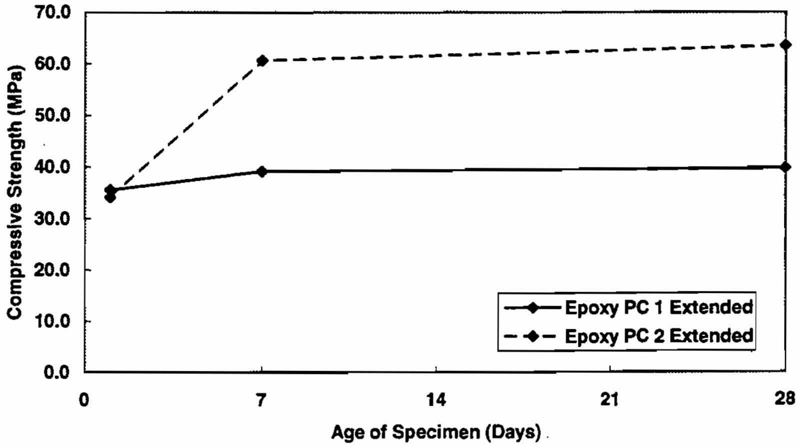


Figure 5.3 Compressive strengths of the epoxy polymer concrete materials

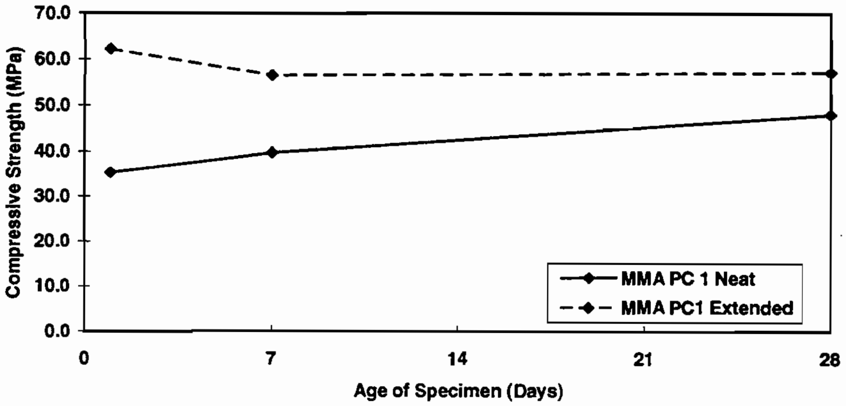


Figure 5.4 Compressive strengths of the methyl methacrylate polymer concrete materials

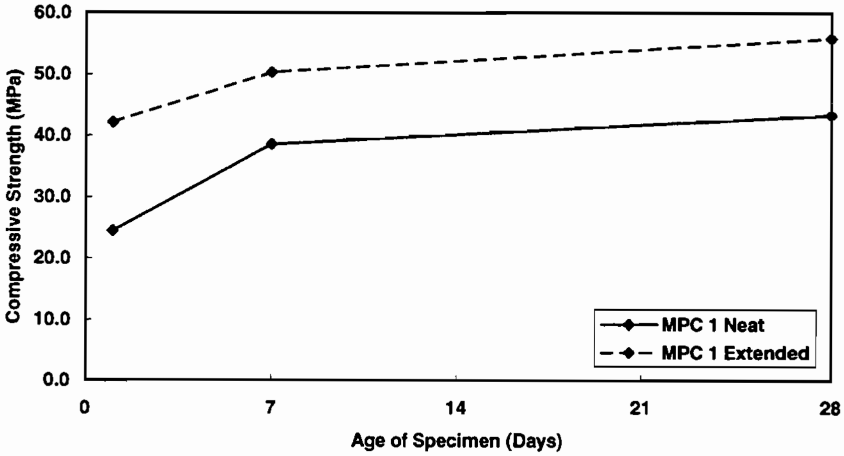


Figure 5.5 Compressive strengths of the latex-modified concrete materials

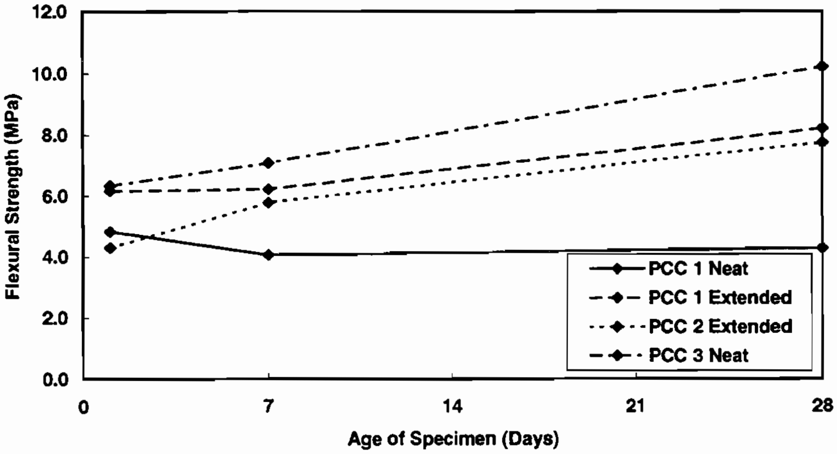


Figure 5.6 Flexural strengths of the portland cement concrete materials

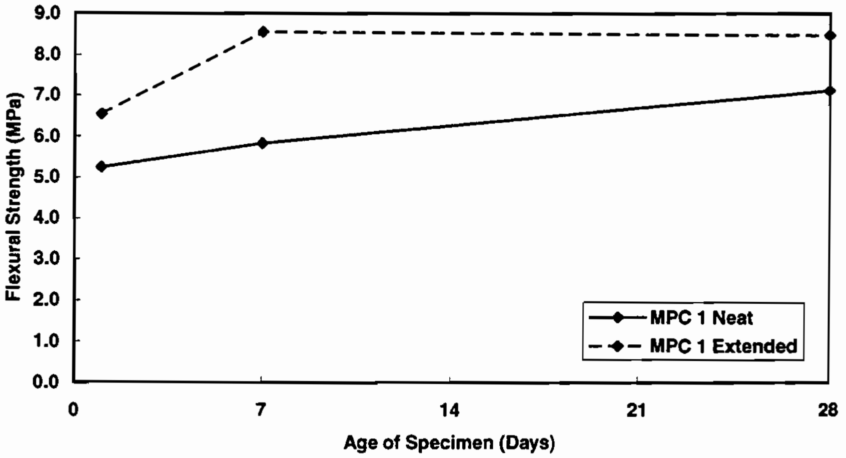


Figure 5.7 Flexural strengths of the magnesium phosphate concrete materials

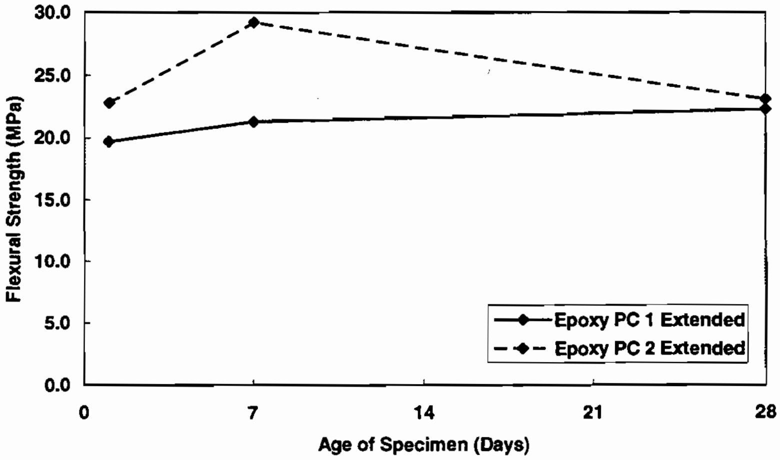


Figure 5.8 Flexural strengths of the epoxy polymer concrete materials

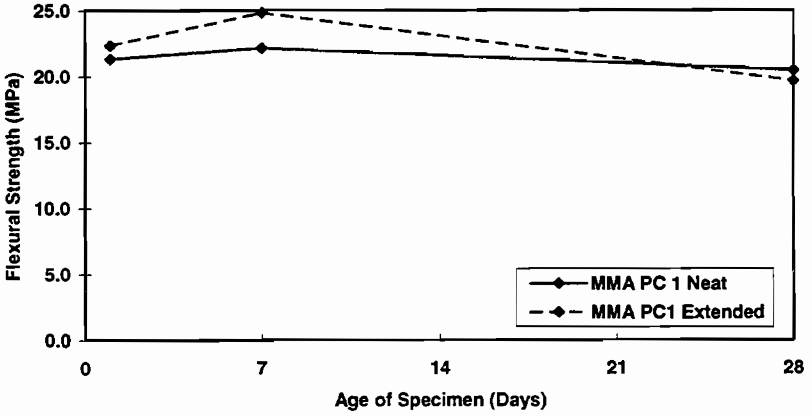


Figure 5.9 Flexural strengths of the methyl methacrylate polymer concrete materials

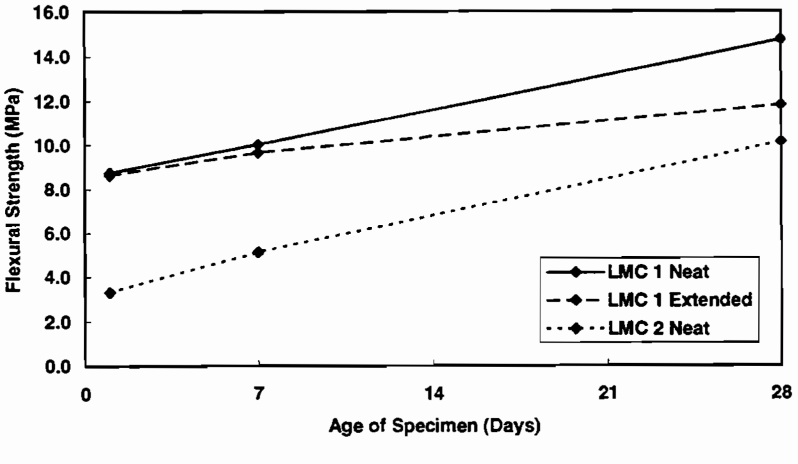


Figure 5.10 Flexural strengths of the latex-modified concrete materials

The moduli of elasticity for the polymer-based materials were much lower than those for the other materials tested. The values ranged from 1 to 3 x 10^{-4} MPa, depending on the amount of aggregate that was added to the mix. For example, the modulus of elasticity for MMA PC increased from 1 to 2.5 x 10^{-4} MPa when we added 34 kg of coarse aggregate to the mix. If a repair material is chosen that has a different modulus of elasticity than the substrate, then the mismatch can ultimately lead to the repair failure. When a repair area will be subjected to a large loading, it may be more beneficial to use a material (e.g., PCC, MPC, or LMC) that is able to more closely match the substrate modulus of elasticity.

The coefficients of thermal expansion for the polymer-based materials were 2 to 3 times larger than those of the other materials tested. The mismatch in coefficient of thermal expansion is of major concern because the potential for large internal stresses to develop if large temperature fluctuations occur is significantly enhanced. If the tensile strength of any part of the repair system is exceeded, failures in the form of cracking and delamination will occur and render the repair useless. The weak link in a polymer-based repair normally occurs at the bond interface, or slightly below it. After the repair is subjected to a number of thermal cycles, the bond becomes fatigued from large internal stresses and causes delamination of the repair material. For young repairs a visual inspection of the repair normally reveals it to be in good condition with no apparent cracks. If further investigation in the form of sounding of the repair is performed, then often a delamination failure becomes easily noticeable. After about two years, the repair can begin to spall over large areas and become completely useless in protecting the substrate. The PCC, MPC, and LMC materials all had coefficients of thermal expansion comparable to that of typical substrate. In general, their measured values were in the range of 4 to 8 x 10^{-6} mm/mm/°C, which is only slightly larger than the value of 6 x 10^{-6} mm/mm/°C measured for typical substrate. The polymer-based materials had values in the range of 12 to 24 x 10^{-6} mm/mm/°C.

A very important consideration in selecting a repair material is determining whether it is dimensionally compatible with the substrate. One way to determine this is to measure the shrinkage the repair material will undergo. Large volume changes will cause internal stresses to develop within the repair material and substrate. The stresses can become larger than the system's capacity and can, as a consequence, cause cracking to occur. A typical shrinkage-versus-time plot is shown in Figure 5.17. Typical of most repair materials, the curve shows how the majority of shrinkage occurs shortly after casting. This is due to most repair materials being rapid-setting materials. Table 5.1 shows the peak shrinkage strains that were obtained. Most of the materials fall within the range of 500 microstrains to 1,000 microstrains. Only the MMA PC fell out of this range, with its much larger value of 2,000 microstrains. This underscores the caution that should be exercised when using an MMA repair material. This should not, however, limit their use, since MMA materials have a performance history as good as or better than that of many PCC materials. For the other materials, there should not be any shrinkage-related problems if proper curing techniques (i.e., those recommended by the manufacturer) are utilized.

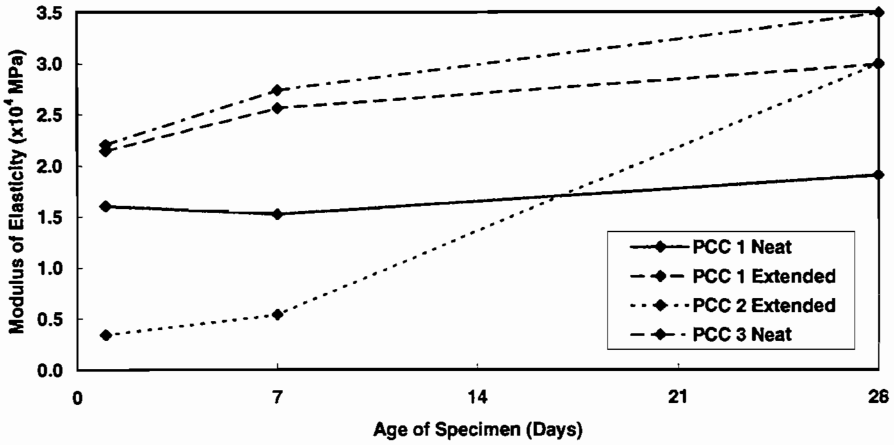


Figure 5.11 Modulus of elasticity of portland cement concrete materials

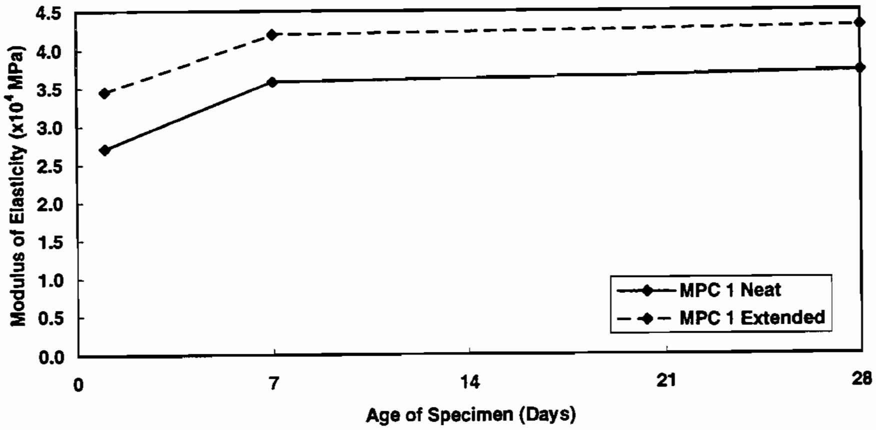


Figure 5.12 Modulus of elasticity of magnesium phosphate concrete materials

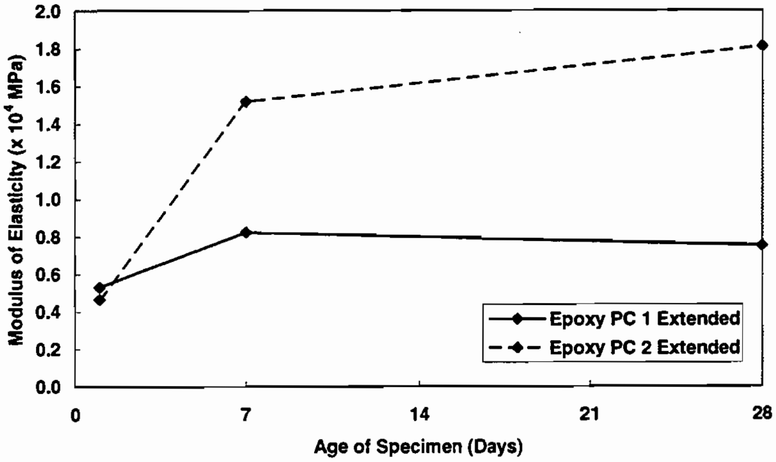


Figure 5.13 Modulus of elasticity of epoxy polymer concrete materials

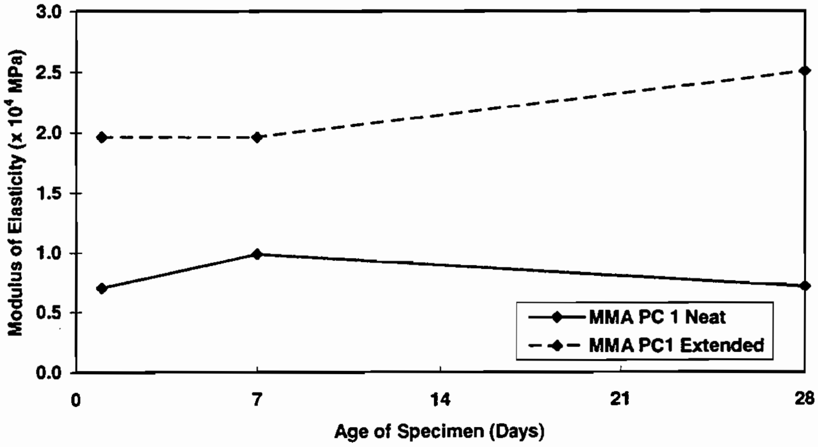


Figure 5.14 Modulus of elasticity of methyl methacrylate polymer concrete materials

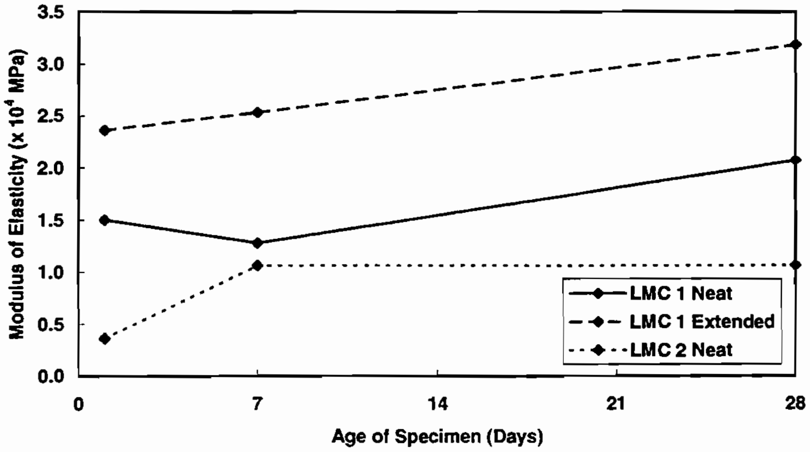


Figure 5.15 Modulus of elasticity of latex-modified concrete materials

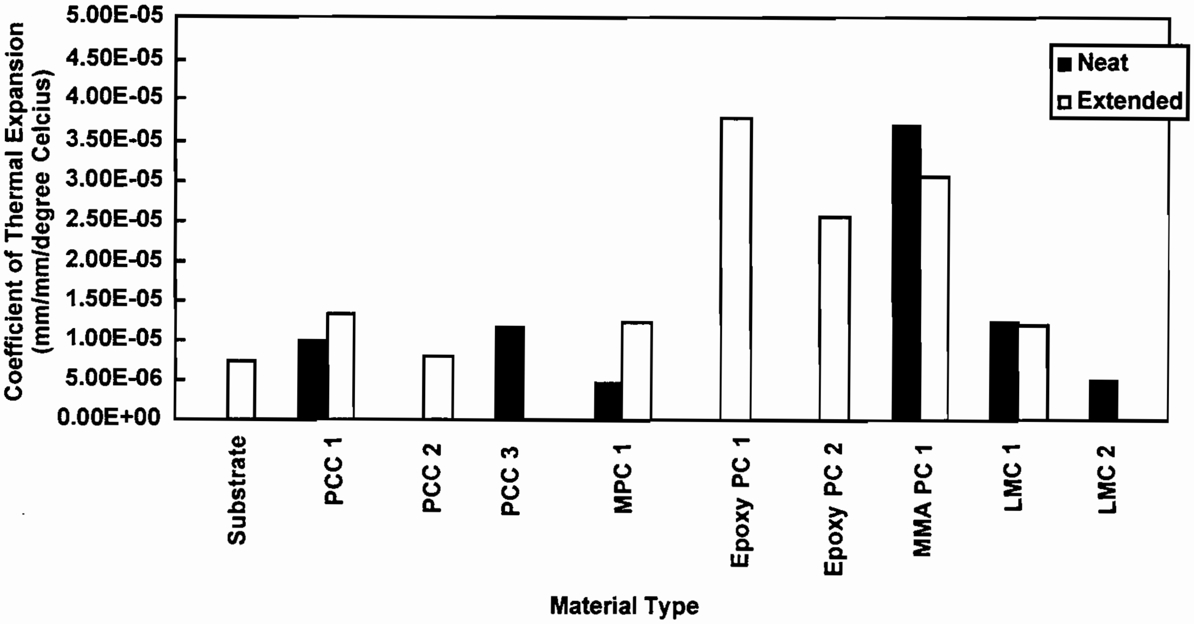


Figure 5.16 Coefficient of thermal expansion test results

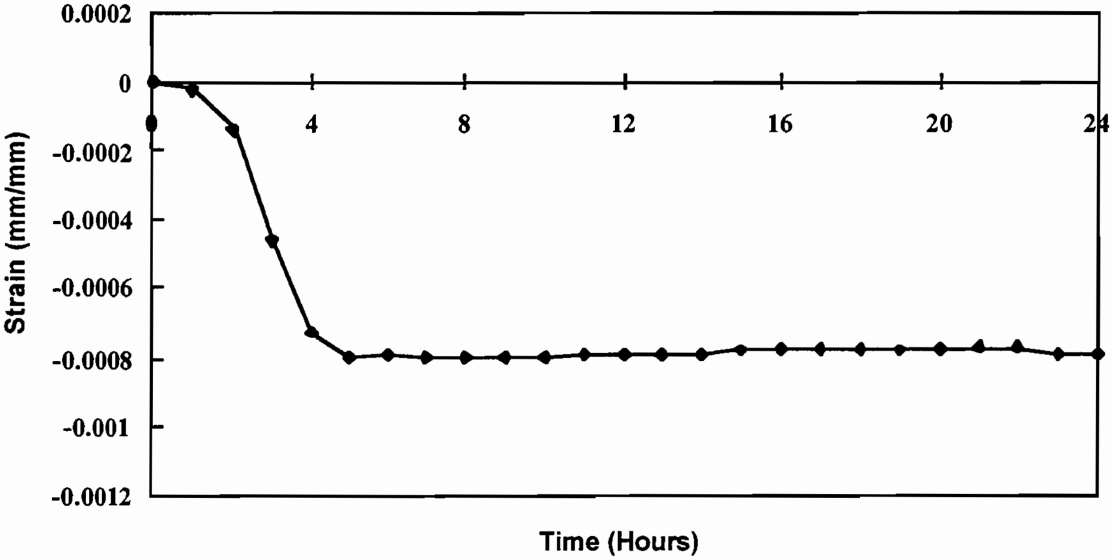


Figure 5.17 Typical shrinkage plot

Table 5.1 Shrinkage strain test results

Material Type	Peak Shrinkage Strain (x 10^{-4} mm/mm)*
PCC 1	-2.6
PCC 2	9.0
PCC 3	8.1
MPC 1	6.1
Epoxy PC 1	6.4
Epoxy PC 2	4.9
MMA PC 1	20.3
LMC 1	7.9
LMC 2	9.8

* + = Contraction
- = Expansion

The factors that determine how well a repair will perform over time are directly related to the bond that is developed between the repair material and substrate. There are two major factors that influence the initial bond strength of a repair: interlock and adhesion (Ref 13). Interlock is a function of the prepared surface roughness. The contribution from interlock is established prior to placing the repair material. A rougher surface will help the development of a stronger bond owing to the increasing surface area that the repair material is able to adhere to.

Adhesion, by contrast, is affected by the chemical bond that is developed during the curing process. As a result, adhesion is influenced by the variables that normally affect paste-aggregate bond (Ref 13). It is also necessary for the repair material to be scrubbed into the substrate to ensure that all the pores in the interface are filled. This can be achieved if quality workmanship and the correct mix type are utilized. The last and often most important consideration is proper curing of the repair material. Curing is vital in developing a strong bond to ensure that microcracking along the interface does not occur.

A major portion of this research project was devoted to evaluating the bond strengths of various types of repair materials. It was found that the majority of the materials tested did not lose significant bond strength when subjected to thermal cycling, up to 1120 cycles. These results were obtained after coring the specimens and conducting pull-off tests after every 4 to 6 weeks of thermal cycles. Most of the specimens were cycled for a minimum of 6 months, with the LMC 1 specimens cycling for nearly 1 year. A typical plot showing the bond strength variation as a function of thermal cycles is shown in Figure 5.18. The plot shows that the initial and final bond strengths have approximately the same values. For some of the materials, their 7-day bond strengths were less than their final recorded bond strengths. This is most likely due to the material being still in the process of gaining bond strength. For these materials, a better representation of the true bond strengths developed would be represented by their 2- or 4-week pull-off strengths.

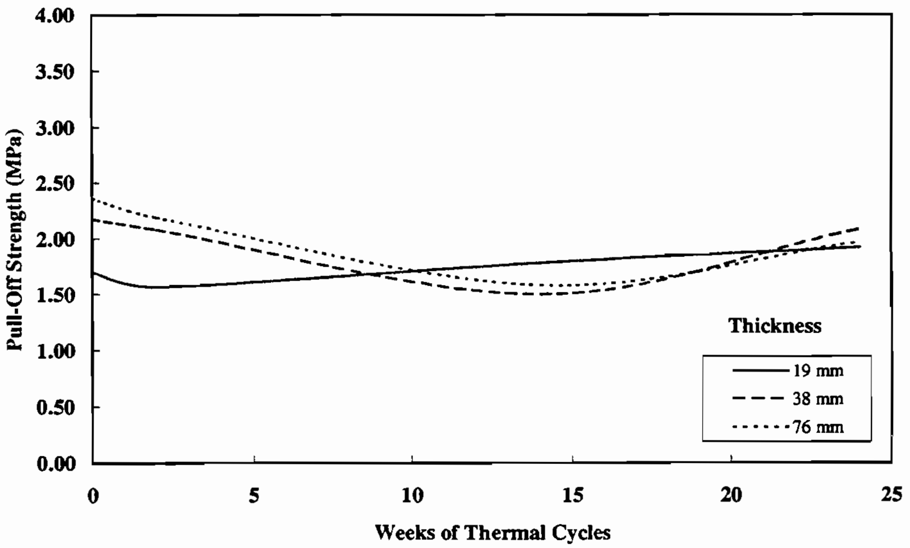


Figure 5.18 Typical bond test results

Even though the bond strengths for most of the different repair materials did not lose strength over time, they did all differ in initial values. Table 5.2 presents the initial and final pull-off strengths and type of failures that occurred. As seen in the table, the PCC and MPC materials typically have pull-off strengths of approximately 2.1 MPa, while the epoxy PC, MMA, and LMC 1 materials have initial strengths of about 3.5 MPa (excluding LMC 2 that experienced cracking while curing and consequently does not give a fair representation of the material category). The higher pull-off strengths for the polymer-based materials do not necessarily suggest that they are a better repair material. The PCC and MPC materials may perform just as well or better than the polymer-based materials, owing to the fact that lower internal stresses will be developed in these materials because they have a higher degree of compatibility with the substrate.

It has been documented that the magnitude of internal stresses developed is affected by the thickness of the repair material (Ref 14). For this study, this effect was not evident, based on the pull-off strengths. One possible reason for this could be that the dimensions of the specimens selected for analysis in this project were such as to restrain the development of significantly larger stresses within the thicker repairs.

During the pull-off test, failure most commonly occurred at the bond interface. The interface is inherently weak as a result of attempting to synthesize two materials into one cohesive system. According to one source, "the bond region is weak because cracks invariably exist at the paste-coarse aggregate interface, even in continuously moist-cured concrete" (Ref 13). Very seldom will the pull-off test fail within the repair material. This reinforces the importance of selecting a repair material that will develop a good bond.

Pull-off failure may also occur within the substrate. One cause for this may be that not all the damaged concrete was properly removed down to sound concrete. Substrate failure may also occur when a polymer-based material is used. The bond strength developed in these materials is quite often stronger than that of the substrate. This was observed for the epoxy and MMA materials evaluated in this study.

The deteriorating mechanism associated with thermal cycling was not observed for the majority of materials evaluated in this project. The following is a list of possible reasons that losses in pull-off strengths were not observed.

- Selection of excellent materials to evaluate
- The temperature ranges chosen to replicate what is typically expected in Texas not severe enough
- The internal stresses developed not large enough to cause loss in strength owing to the repair material being compatible with the substrate and/or the stresses not large enough to reach the material's capacity
- The number of thermal cycles chosen to represent a typical Texas repair not sufficient to cause deterioration in specimens

Table 5.2 Results of bond strength test

		Initial		Final		
Material Type	**Thickness (mm)**	**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

The only material to fail during thermal cycling was the Epoxy PC 1 neat mix. For this mix, two different thicknesses — 6 mm and 19 mm — were cast. The 19-mm thickness failed immediately after casting, delaminating within the substrate. It was not even possible to obtain an initial bond strength at 7 days because the bond was too weak and failed as a result of coring action. For the 6-mm neat specimens, failure took place within 14 weeks of thermal cycling. This failure occurred after the specimen had achieved an initial bond strength of 3.7 MPa. This failure supports the theory that large differences in CTE can cause the deterioration of bond strength. This loss in pull-off strength was not observed for the Epoxy PC 1 mixes that were extended with 13.6 kg of sand. Based on these results, additional mixes have been cast that contain varying amounts of sand. The original and additional Epoxy PC 1 mixes that have been cast are shown in Table 5.3. A highlighted cell indicates that a specimen with this thickness and polymer-to-sand ratio has been cast. Also, 25-mm x 30-mm beams were cast to determine the coefficient of thermal expansion of the different epoxy mixes (Table 5.4).

While early pull-off strengths have been obtained for these specimens, it is too early to draw any conclusions from the results. The specimens will be allowed to continue to cycle in the thermal chamber, and the pull-off strengths will be monitored for the duration of the project. The results will be presented in the next project report.

Table 5.3 Epoxy PC 1 original and additional epoxy mix designs

Epoxy-Sand Ratio				
	Original Mixes		Additional Mixes	
	Mix 1	Mix 2	Mix 3	Mix 4
Thickness (mm)	1.00	0.21	0.64	0.43
6	▨	▨	▨	▨
19	▨	▨	▨	—
38	—	—	—	▨
76	—	—	—	

Table 5.4 Coefficient of thermal expansion of original and additional epoxy mixes

Polymer / Sand Ratio	CTE (x 10^{-6} mm/mm/°C)
1.00	130
0.64	90
0.21	54
0.43	38

5.4 DURABILITY PROPERTY RESULTS

The durability properties tested were permeability, abrasion, and absorption. The permeability results were classified according to the ranges established in AASHTO T277 (Table 5.5). It is more useful for the information to be presented as a range rather than as just a specific number. The permeability results are shown in Table 5.6. The abrasion and absorption results are presented in Figures 5.19 and 5.20, respectively.

The permeability results came out as expected, with the polymer-based materials all receiving a "negligible" ranking. The next most impermeable material was LMC 1. The LMC 2, falling in the range of "high," is misleading because the mix was extremely viscous and contained a large water content. The ranking of "very low" for LMC 1 better represents this material category. A surprising result is that the MPC material tested received a "high" ranking for both its neat and extended mixes. More tests would need to be conducted in order to determine whether this is characteristic of this particular material or for all MPC-based products.

The polymer-based materials performed best during the abrasion test. The LMC and PCC materials both performed similarly, with little noticeable difference in their weight losses. The MPC lost the most material when subjected to the sandblasting. An interesting observation is that only the PCC 3 and the polymer-based materials performed better than the substrate. This may be due to the type, size, and amount of aggregate used in the mix. For the absorption test, the epoxy, MMA and LMC materials outperformed the PCC and MPC materials. The polymer-based materials all had negligible amounts of weight increase after having been soaked in water, as compared with the PCC materials, which increased by 5 to 7 percent in weight.

From the results, the best material for a particular repair depends on the environmental conditions it will be subjected to during its lifetime. For the most part, the polymer-based materials, as expected, exhibited exceptional durability properties. If a repair will be subjected to a harsh environment, then it may be beneficial to select a polymer-based material that will better protect the parent concrete. On the other hand, if there is little likelihood of deterioration, then a PCC or MPC would be acceptable and would not cause any problems associated with a mismatch in compatibility properties. The durability properties, in general, from best to worst, are polymer-based materials, LMC, PCC, and MPC.

Table 5.5 Permeability classifications

Charge Passed (Coulombs)	**Chloride Ion Penetrability**
> 4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very Low
< 100	Negligible

Table 5.6 Permeability test results

Material	**Mix Type**	
	Neat	**Extended**
Substrate	N/A	Low
PCC 1	Low	Moderate
PCC 2	N/A	High
PCC 3	Very Low	N/A
MPC 1	High	High
Epoxy PC 1	N/A	Negligible
Epoxy PC 1	N/A	Negligible
MMA PC 1	Negligible	Negligible
LMC 1	Very Low	Very Low
LMC 2	High	N/A

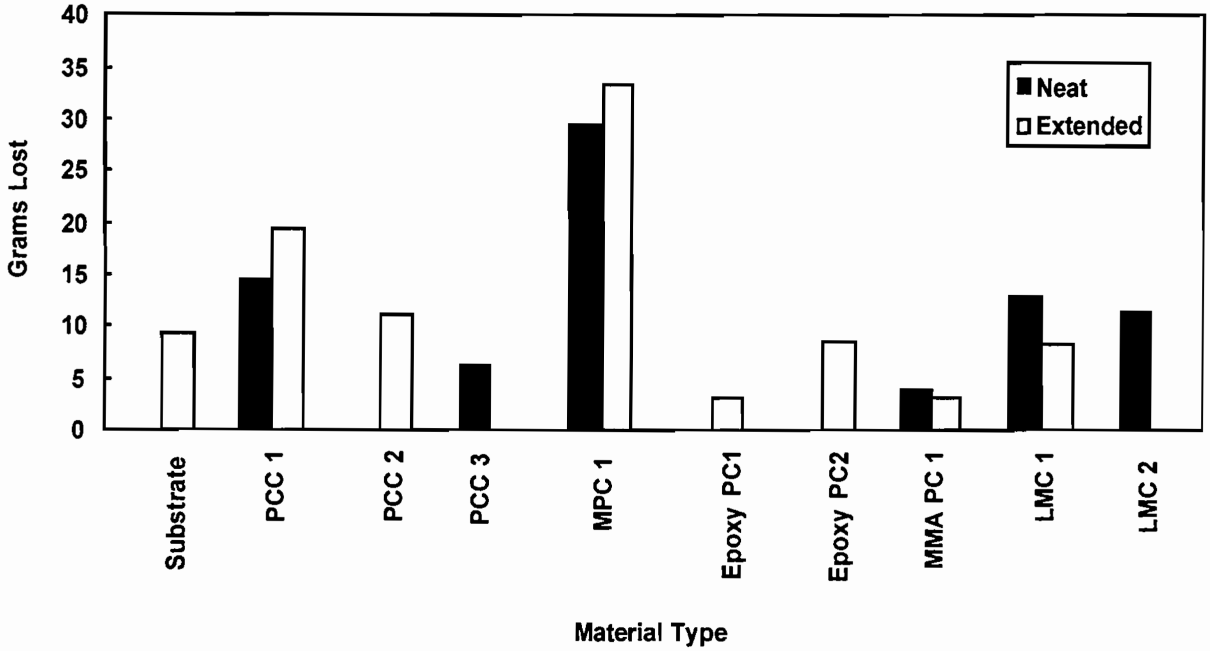


Figure 5.19 Abrasion test results

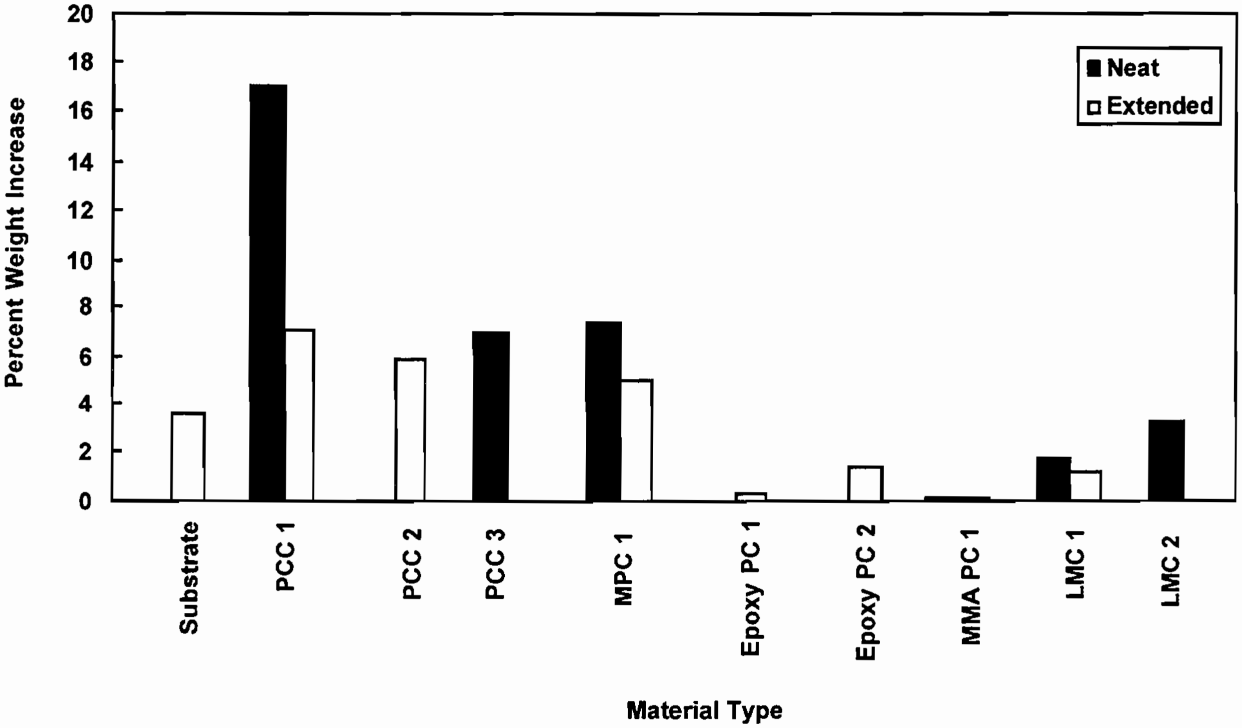


Figure 5.20 Absorption test results

5.5 DISCUSSION OF RESULTS

Most of the discussion of the test results was presented within the first three sections. The material property test results reveal that each material category has its strengths and weaknesses. Table 5.7, a comprehensive comparison of the repair materials, ranks the performance within each material category. A ranking of "1" means that the material is the highest or lowest within that category, depending on the material property evaluated. For the mechanical properties, modulus of elasticity, and initial bond strength, a ranking of "1" corresponds to the highest value. For the remainder of the properties, a ranking of "1" corresponds to the lowest value in the category. The ranking procedure used for each category is indicated in Table 5.7.

An attempt was made to relate the bond strength of the different repair materials to the tested material properties. The bond strengths used in the analysis are listed previously in Table 5.2. To help facilitate this process, a step-wise statistical analysis was performed using the SAS program. We also used the *Excel* computer program in developing the relationships. The primary objectives were to develop a general regression model and to gain more insight into the interrelationships between bond strength and the factors that most influence its performance. The variables that were screened for acceptance into the statistical model were the material properties evaluated and discussed previously, with the additions of the effects of thickness and aggregate added to the mix. To determine the most significant material properties that should be included in the model, the following steps were performed.

(1) Individual property tests and interaction terms were plotted versus the performance variable, bond strength. Both linear and logarithmic plots were created to determine if any trends in performance became apparent.

(2) Linear and logarithmic regression analyses were conducted based on the properties that were found to be most applicable by step 1.

(3) The results obtained in steps 1 and 2 were compared and any apparent discrepancies were resolved through engineering knowledge.

(4) It was then determined which property tests, if any, could be used as a means to predict bond strength.

Based on information received from the first two steps, the material properties that appeared to best predict bond strength are flexural strength and modulus of elasticity. The inclusion of both of these variables is logical because polymer-based materials typically have high bond strengths and large differences in these two properties compared to that of cementitious materials. The most important relationships based on the repair materials evaluated in this project were that materials with higher bond strengths typically had lower modulus of elasticity values and higher tensile strengths than those materials with lower bond strength. Figure 5.21 is a plot of bond strength versus the tensile strength. Although there is much scatter in the data, a linear relationship appears to be present. One material type that does not fit well into the model is LMC materials. This material is capable of simultaneously having a relatively high bond strength while maintaining property values comparable to those of ordinary concrete.

The modulus of elasticity did not predict bond strength as well as flexural strength, but as a general trend the materials with higher bond strengths had lower modulus of elasticity values. When property interaction terms and combinations were analyzed, the coefficient of determination remained approximately the same.

It was difficult to establish a relationship for the bond strength as a function of thermal cycles. The same material properties screened previously were used again for this statistical analysis. One of the problems is the difficulty in achieving consistent pull-off strength values owing to there being a reasonably high variability in the results. This is because there are many different factors that can ultimately influence the value. The following is a list of the most significant factors that can lead to discrepancies in the results.

- Experience of the operator
- Material variability in strength
- Type and quality of equipment used to perform the test
- Rate the concrete is cored and the pull-off test are administered
- Eccentricity of cores

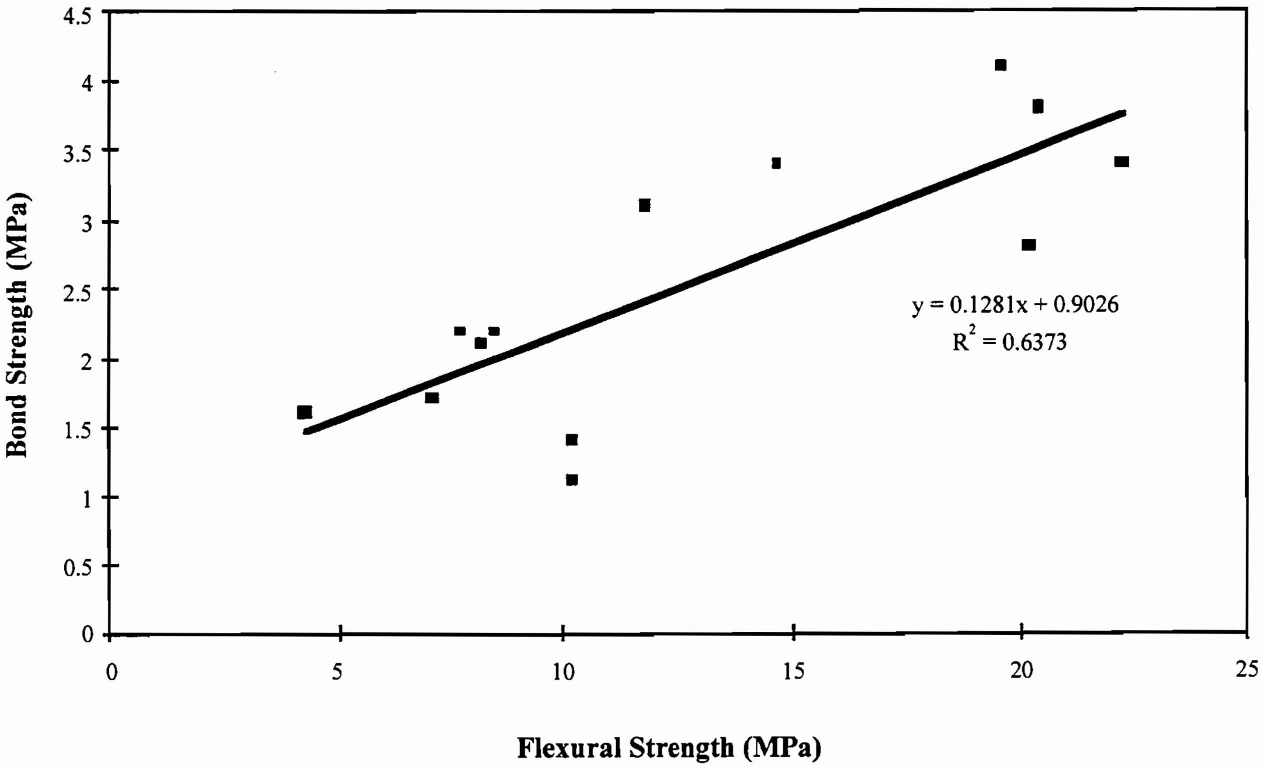


Figure 5.21 Regression analysis of bond strength

Often deciphering between a loss in strength and normal variance in readings can be extremely difficult. It was found that pull-off strengths performed on the same material can differ by as much as 0.3 MPa to 0.5 MPa for values of 3 MPa to 4 MPa. This leads to the possibility of a 3 to 12 percent error. This is due to both the scale of the pull-off tester and to reasons listed previously. Observing small changes in strength is virtually impossible owing to the precision of the test. The test method should only be regarded as useful in observing larger losses in strength. The strengths should be thought of as representing a range rather than a specific value. As a result, caution should be exercised when using a material's bond strength, unless it is possible to perform a large number of pull-off tests that will enable a statistically significant value to be obtained.

While it was difficult to use the pull-off test to measure small bond strength losses as discussed above, the procedure may lend itself well to a quality control and quality assurance test (QC/QA). Currently there is very little to no control over the quality of concrete repairs. Often an outside contractor performs the repairs using a specified material type with no quantitative evaluation of the repair. If a minimum pull-off strength and variability was established prior to performing the repair, then the QC/QA pull-off test could be used to verify that the repair satisfied the requirements.

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

CHAPTER 6. FIELD EVALUATION PROGRAM

6.1 INTRODUCTION

The field evaluation program was conducted in order to obtain a more thorough understanding of the repair process. While the results from the laboratory evaluation program are instrumental in creating performance criteria for repair materials, the test results are limited. No matter how carefully a laboratory test is performed, there will always remain differences between the model and the environment it is attempting to replicate. The objective of this program was to evaluate, both qualitatively and quantitatively, the performance of existing repairs throughout the state of Texas. By evaluating the repairs it was possible to observe conditions that cannot be reproduced in the laboratory. The next section describes the information gathered during the field evaluation visits.

6.2 SELECTION CRITERIA FOR REPAIR LOCATIONS

The first steps in the field evaluation program were to obtain candidate field sites and then to select the sites to be visited. With the assistance of TxDOT Materials and Tests Division engineers, it was possible to compile a list of potential locations. Most of these locations were recommended because the engineer had personal involvement with the project. This made it possible to obtain pertinent background information about the repair work. The actual sites were selected to investigate a wide range of typical repairs that can be expected in Texas (Figure 6.1). In order to ensure diversity among repair sites, each potential location was categorized according to the following criteria:

(1) *Environmental Conditions.* The state of Texas was divided into different regions based on such things as the occurrence of freeze-thaw, ranges of thermal cycles, and deterioration from exposure to salt air or water.

(2) *Type of Repair Material.* The type of material used in the repair was placed within the classification system established in Chapter 3. An attempt was made to include as many different types of repair materials as possible.

(3) *Orientation of Repair Work.* A repair site was classified as horizontal, vertical, or overhead.

(4) *Age of Repair.* It was important to evaluate repairs of different ages to help determine the effect of time on performance.

At each repair location, both qualitative and quantitative data were obtained. The qualitative portion of the program consisted of gathering pertinent background information, on-site information, and a visual inspection of the performance (Table 6.1). The quantitative part of the program consisted of determining the bond strength of the repair material by coring and conducting pull-off tests at each repair location (a procedure described in section 4.4.4). From the pull-off tests it was possible to determine how the repairs were performing. The following sections summarize the results obtained from the field evaluation program.

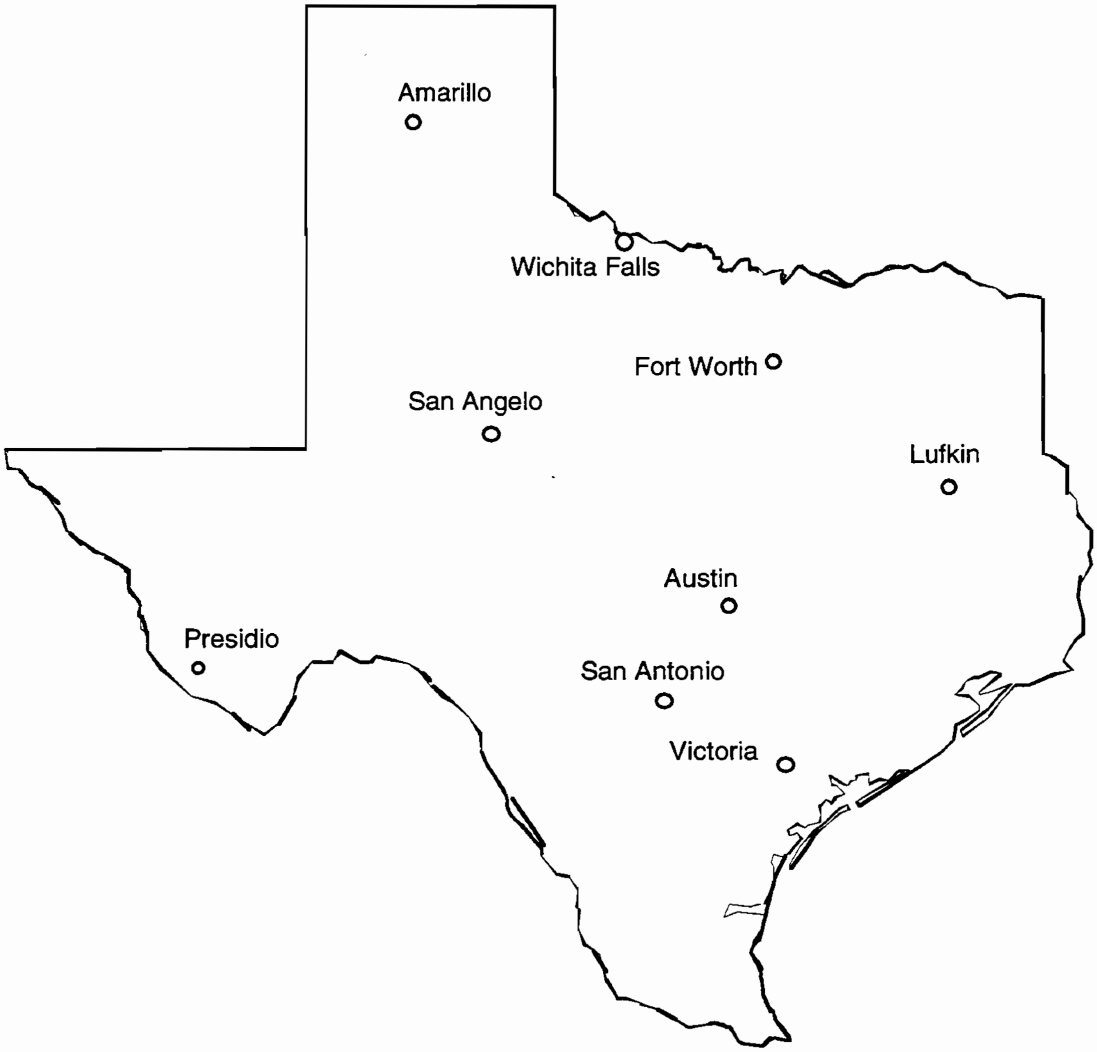


Figure 6.1 Locations investigated during the field evaluation program

Table 6.1 Qualitative information recorded

Background Information	On-Site Information	Visual Inspection
Geographic Location Age of Repair Repair Material Orientation of Repair Method of Application Climatic Conditions (During Placement)	Geometry of Repair (Thickness, Volume, Surface Area) Exposure Conditions	Durability Problems Aesthetics Workmanship Debonding

6.3 AUSTIN SITE VISIT

Three separate sites were evaluated in Austin, denoted as Austin No. 1, No. 2 and No. 3.

6.3.1 Austin No. 1

The first repair evaluated was on a bridge deck located on northbound MoPac near the 2222 entrance ramp. The original damage at this location was caused by excessively grinding down a hump in the road, leaving a depth of about 10 mm over an area of about 1.5 m by 3.0 m. The repair material evaluated was the second one used at this location, the first material (hydraulic mortar) having previously failed. The repair was made in 1976. Based on a visual inspection, the MMA PC was in good condition with the exception of raveling occurring along one of its edges. The average pull-off strength obtained was 1.2 MPa, with a standard deviation (σ) of 0.1 MPa. This value is lower than what would be expected for an MMA-based material. It is possible that the repair has lost some bond strength owing to the mismatch in material properties between the repair and substrate materials. However, the results are very good considering the fact that the repair has been in place for 20 years. The difference in material properties is more of a factor for this repair because it is located on a bridge deck where large temperature gradients occur.

Table 6.2 Background information for Austin No. 1

Desired Information	Description
Geographic Location	Northbound on MoPac (Loop 1) at the 2222 entrance ramp
Age of Repair	20 Years
Repair Location	Top of bridge deck
Repair Material	Sand placed with MMA poured over the top
Orientation	Horizontal
Repair Thickness	$\cong$ 10 mm
Exposure Conditions	Subjected to direct traffic loading and environmental conditions

6.3.2 Austin No. 2

The original source of damage was similar to that found at location No. 1. Excessive grinding in the roadway had resulted in a need for repair work. This overlay is located on the interchange from northbound MoPac Boulevard (Loop 1) to US 183 north. Reportedly, excessive water was added to the latex-modified concrete used to make the repair. The thickness of the overlay varied from 25 mm to 76 mm in depth. A visual inspection found no signs of deterioration, such as delamination, abrasion, or cracking. The average pull-off strength was 1.0 MPa ($\sigma = 0.4$), with the failures occurring at the interface. Figure 6.2 shows a pull-off test being conducted.

6.3.3 Austin No. 3

The Austin No. 3 repair is located at the Williams Street Overpass along IH-35 in Georgetown. A 762-mm diameter column located in the center divider had been struck 10 years earlier by a truck, which caused both impact and fire damage. In order to reach sound concrete, concrete was removed to the reinforcing steel (51 mm deep). An epoxy primer was placed first, followed by an epoxy material (TxDOT Type VIII extended with sand). A quick-setting cementitious material was then placed over the repair material to level the surface. The thickness of the leveling material varied from negligible to approximately 32 mm. A weatherproofing cover was then placed over the entire column surface. There were numerous cracks in the repair material (Figure 6.3). The first sign of cracking occurred about 2 years after the repair was performed. There was also a section approximately 100 mm by 150 mm that had completely spalled. By sounding the concrete with a hammer it was determined that a significant portion of the repair had become delaminated. Six pull-off tests were conducted on regions where sound concrete was found. The average bond strength was determined to be 0.9 MPa ($\sigma = 0.2$), with all failures occurring along the bond interface.

Table 6.3 Background information for Austin No. 2

Desired Information	Description
Geographic Location	Northbound MoPac to 183 interchange
Age of Repair	3 Years
Repair Location	Top of a bridge deck
Repair Material	Latex-modified
Orientation	Horizontal
Repair Thickness	≅ 25 mm to 76 mm
Exposure Conditions	Subjected to direct traffic loading and environmental conditions

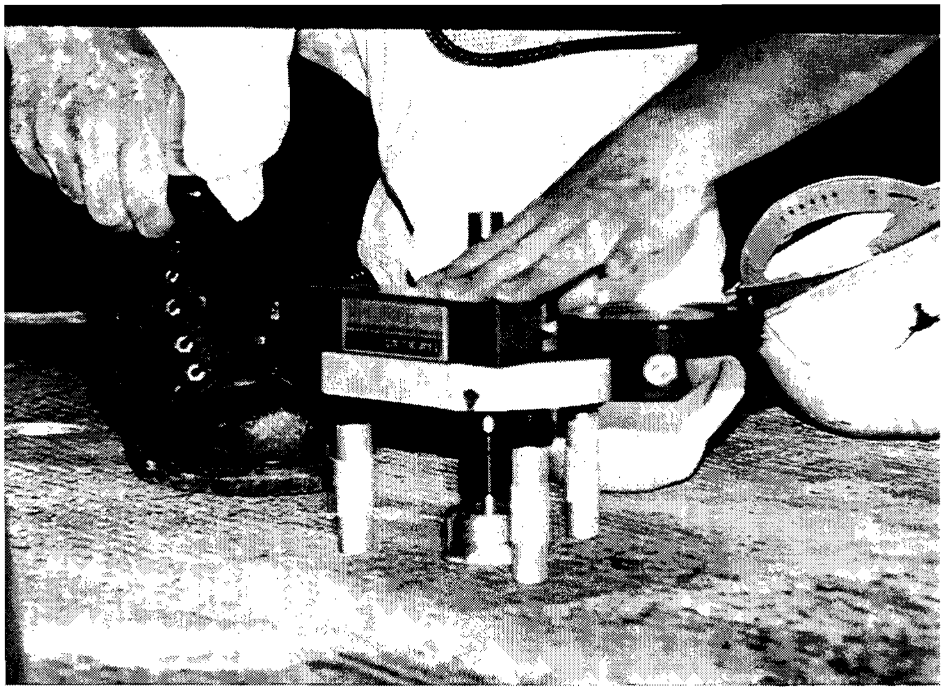


Figure 6.2 Pull-off test being conducted on horizontal surface — Austin No. 2

Table 6.4 Background information for Austin No. 3

Desired Information	Description
Geographic Location	Williams St. Overpass over Interstate 35
Age of Repair	10 Years
Repair Location	Column
Repair Material	Epoxy and cementitious
Orientation	Vertical
Repair Thickness	51 mm to 76 mm
Exposure Conditions	Protected by bridge deck

Figure 6.3 Cracking and spalling of repaired column — Austin No. 3

6.4 SAN ANTONIO SITE VISIT

For this site visit, we evaluated typical repairs that are made at precast concrete plants. It is not uncommon for precast concrete members to be damaged during the fabrication process (the damage often occurs during form removal or transport). It is important for these damaged members to be repaired for both aesthetic and durability reasons. For this site visit, prestressed panels were evaluated at locations where the rebar, used exclusively for lifting purposes, had ripped out during transport (Figure 6.4).

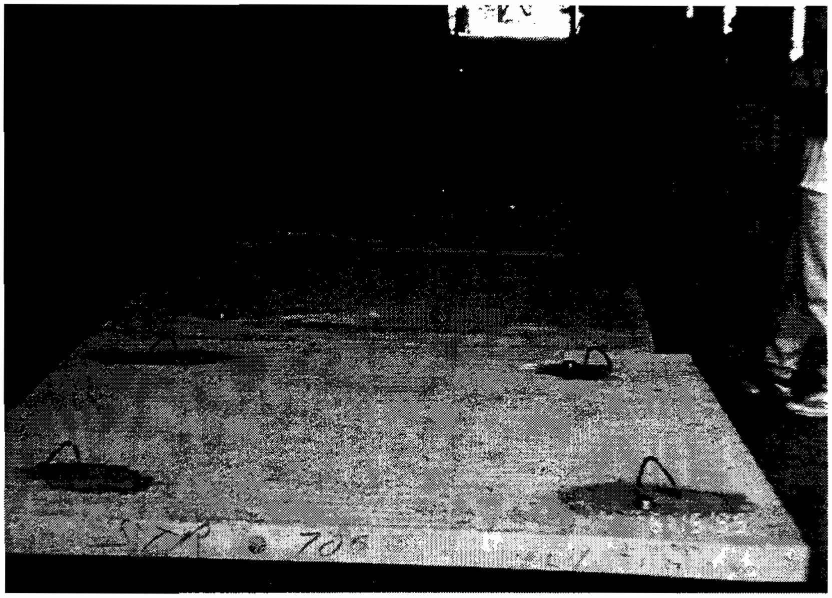


Figure 6.4 Repaired prestressed panels — San Antonio

There were no specified mixture proportions of epoxy mortar used for the repairs; the mixture proportions were based on adding dry sand to the epoxy until the desired working consistency was reached. The pull-off strengths varied from 0.2 MPa to 1.0 MPa ($\sigma = 0.4$). The large variations were likely caused by the variability in the amount of sand added. All the cores failed close to the surface in the repair material.

Table 6.5 Background information for San Antonio

Desired Information	Description
Geographic Location	Prestressing plant
Age of Repair	2 to 3 Months
Repair Location	Prestress panel
Repair Material	Epoxy extended with sand
Orientation	Horizontal
Repair Thickness	0 mm to 75 mm
Exposure Conditions	Stored in a shed

6.5 AMARILLO SITE VISIT

The repair evaluated was located on the underside of a bridge overpass along US 287 (Figure 6.5). The damage was caused by spalling of the columns, pier caps, and backwalls. The primary purposes of the repairs were for protection of the exposed reinforcing steel and for cosmetic reasons. It appeared that an epoxy bonding agent was applied initially on the substrate before a cementitious repair material was trowelled onto the damaged area. It is also assumed that the repair material was applied in two lifts. This assumption was made after we analyzed the cores and noticed a slight color differentiation at approximately mid-depth. The repair system also consisted of a thin layer of waterproofing on the exterior of the repair areas. The repairs were in poor condition, with large areas spalled off. Six pull-off tests were made on a pier cap where the repair orientation was vertical. The bond strengths were very low, failing at an average value of 0.3 MPa ($\sigma = 0.04$) at the interface. The primary reason for the low pull-off strengths appeared to be poor consolidation. There were large voids (up to 25 mm wide) present within the repair material, particularly at the interface. It is possible that the mix proportions used for the repair were not well suited for the necessary vertical application. An attempt to core a repaired backwall proved unsuccessful owing to the weakness of the material.

Table 6.6 Background information for Amarillo

Desired Information	Description
Geographic Location	Highway 287
Age of Repair	7 to 8 Years
Repair Location	Columns, pier caps
Repair Material	Cementitious
Orientation	Vertical and overhead
Repair Thickness	≅ 50 mm
Exposure Conditions	Protected by bridge deck, located in freeze-thaw region

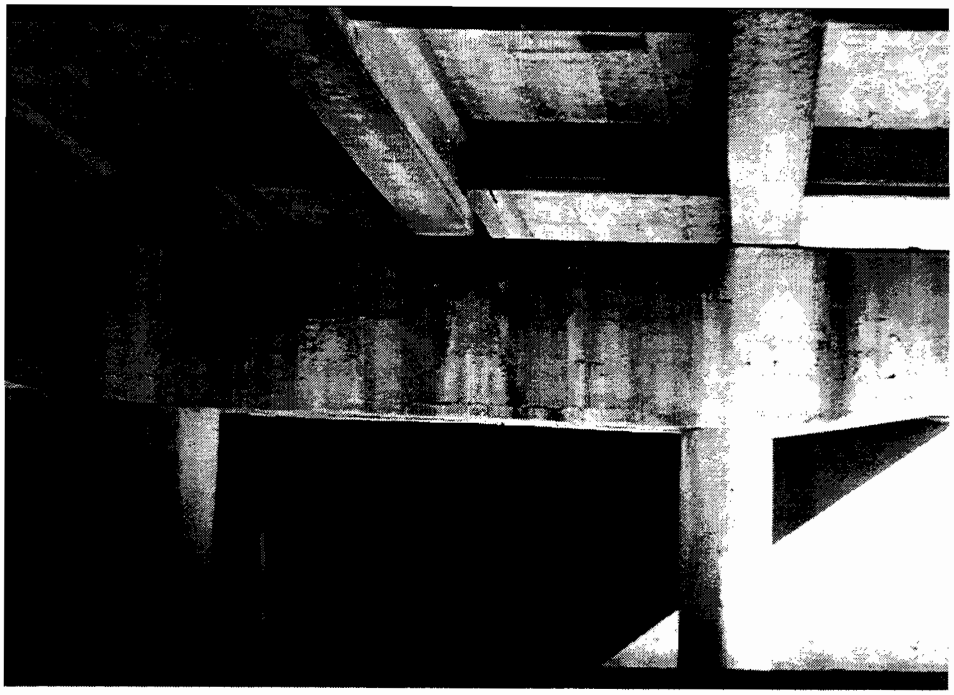


Figure 6.5 Typical spalling located on pier caps — Amarillo

6.6 FORT WORTH SITE VISIT

There were two separate sites evaluated in Fort Worth, denoted as Fort Worth No. 1 and No. 2.

6.6.1 Fort Worth No. 1

The repairs are located on the University Drive entrance ramp onto westbound Interstate 30. The repairs consisted of polymer and epoxy overlays placed over deteriorated portland cement concrete. There were eleven different types of materials present on the entrance ramp. The different materials had been used because the overlays were part of an earlier study (Ref 15). During the site visit, pull-off tests were conducted on eight of the materials (five polyester-urethane [PU] materials and three epoxy materials). The results for the performance of each of the materials are presented in Table 6.6.

Table 6.7 Performance evaluations of overlays at University Drive

Material Type	Visual Evaluation	Average Pull-Off Strength (MPa)	Standard Deviation (MPa)
PU-1	Some abrasion	3.8	1.6
PU-2	Map cracking, some abrasion	2.0	0.0
PU-3	Some abrasion	4.2	0.9
PU-4	Map cracking	1.0	0.1
PU-5	Significant abrasion, sections delaminated	0.5	0.2
Epoxy-1	Sections delaminated	4.1	0.2
Epoxy-2	Significant abrasion	1.3	0.9
Epoxy-3	Some abrasion	3.6	0.1

As the results of the pull-off tests reveal, the materials exhibited a wide range of bond strengths. The large variance is due to different material types being used in the repair work. Even though there appear to be large discrepancies in the pull-off strengths, within each material type the pull-off strengths were in close agreement. For example, the pull-off strengths for PU-4 were 1.0 MPa, 1.0 MPa, and 0.9 MPa; for Epoxy-3 they were 3.7 MPa and 3.5 MPa. All the pull-off failures occurred at the bond interface except for PU-4, where the failures occurred within the repair material. Reviewing the values obtained from the pull-off tests, it becomes apparent that it is possible to obtain an overlay that can have a range of possible bond strengths. In order to ensure that a strong bond is developed between the overlay and substrate, extreme caution must be taken to select the correct repair material formulation. It should be chosen based on the environmental conditions that it will encounter during its lifetime.

The visual inspection of the overlays revealed that some of the materials exhibited durability problems (Figures 6.6 through 6.8). While cracking and delaminations are common problems for polymer-based materials, abrasion is not. The amount of abrasion for the overlays ranged from negligible up to 9-mm deep. Some of the overlays exhibited significant map cracking. Aside from being aesthetically displeasing, it did not present any significant durability problems. This is because the cracks were relatively shallow and did not penetrate completely through the overlay. The other type of durability problem present was overlay delamination. This will cause serious problems because an overlay that becomes debonded from the substrate can no longer fully protect the substrate surface from such things as water intrusion or salt penetration. Another problem with an overlay losing its bond is that the repair system no longer acts together as a system. This can cause the overlay to become a traffic hazard (as the material loosens from the rest of the repair).

Table 6.8 Background information for Fort Worth No. 1

Desired Information	Description
Geographic Location	University Drive entrance ramp onto Westbound Interstate 30
Age of Repair	5 Years
Repair Location	Top of bridge deck
Repair Material	PU and epoxy
Orientation	Horizontal
Repair Thickness	6 mm to 10 mm
Exposure Conditions	Subjected to direct traffic loading and environmental conditions

Figure 6.6 Map cracking of overlay — Fort Worth No. 1

Figure 6.7 Delamination of overlay — Fort Worth No. 1

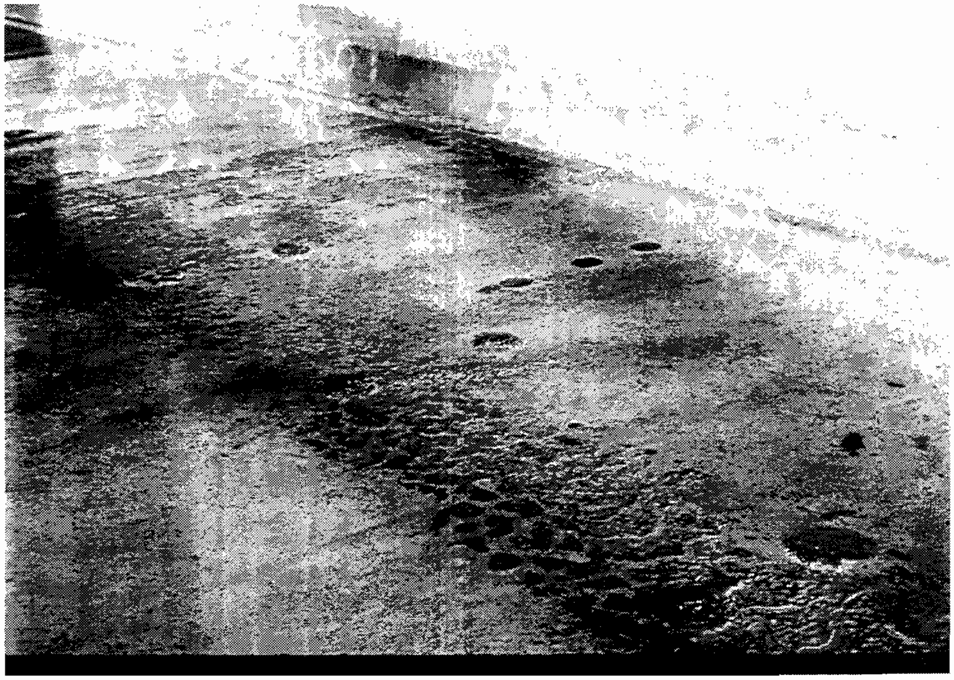


Figure 6.8 Abrasion of overlay — Fort Worth No. 1

6.6.2 Fort Worth No. 2

The repair materials and types of repairs evaluated at Fort Worth No. 2 are very similar to those at No. 1. The repairs at location No. 2 were part of the same experimental program that included location No. 1. The overlays are located at the Ripy Street Overpass over Interstate Highway 35. There were four different types of materials used in the repairs (one epoxy, two polyester-urethane, and one polyester). All four of the materials were evaluated during the site visit. The materials used for these overlays were more aesthetically pleasing than those at location No. 1 and showed no signs of deterioration. The difference in appearance between the two locations could be the result of different application methods. The premix method using sand and gravel was used at location No. 1, while the multi-layer method (broom and seed) with trap rock was used at location No. 2. Table 6.9 summarizes the results.

Table 6.9 Performance evaluations of overlays at Ripy Street

Material Type	**Visual Evaluation**	**Average Pull-Off Strength (MPa)**	**Standard Deviation (MPa)**
Epoxy	Excellent	2.9	0.6
PU-1	Excellent	3.3	0.4
PU-2	Excellent	2.8	0.5
Polyester	Excellent	2.2	0.3

The pull-off strengths of the different materials had high values. There was also less variance in bond strengths between the different materials. One large difference between the overlays at Fort Worth location No. 1 and No. 2 is the volume and type of traffic at the two sites.

Location No. 1 is an on-ramp to a heavily traveled interstate, while location No. 2 is within a school zone that has stop signs in both directions. Even when taking the different types of loading conditions into account, the material types used at location No. 2 appeared to be better than those at location No. 1. This is based not only on bond strength results, but also on the fact that there were no durability problems present in any of the materials.

Table 6.10 Background information for Fort Worth No. 2

Desired Information	Description
Geographic Location	Ripy Street overpass over Interstate 35
Age of Repair	4 years
Repair Location	Top of bridge deck
Repair Material	PU and epoxy
Orientation	Horizontal
Repair Thickness	6 mm to 10 mm
Exposure Conditions	Subjected to direct traffic loading and environmental conditions

6.7 WICHITA FALLS SITE VISIT

There were two separate sites evaluated in Wichita Falls, designated as Wichita Falls No. 1 and No. 2. Location No. 2 actually represents two separate sites, with the results being consolidated owing to the similarities in the types of repairs.

6.7.1 Wichita Falls No. 1

The repairs evaluated were located on the underside of the Scott Street Bridge that spans the Big Wichita River. The work was a year old and consisted of repairing deteriorated concrete as part of normal maintenance. The damaged areas were on the backwalls and arches. The depths of most of the repairs varied from 6 mm to 25 mm, with a few full-depth repairs. A latex-modified material was used in the repairs with an epoxy grout placed over the exposed surface. The workmanship of the repairs was excellent, and there were no signs of deterioration or large voids present along the bond interface. The average pull-off strength was 0.9 MPa ($\sigma = 0.3$), with all failures occurring at the bond interface.

Table 6.11 Background information for Wichita Falls No. 1

Desired Information	Description
Geographic Location	Scott St. over Big Wichita River
Age of Repair	1 Year
Repair Location	Arches, backwalls
Repair Material	Latex-modified
Orientation	Vertical
Repair Thickness	6 mm to 25 mm and full depth
Exposure Conditions	Protected by bridge deck

6.7.2 Wichita Falls No. 2

Repairs at location No. 2 consisted of overlays placed over deteriorated bridge decks. The repairs are located at the Scott Street Overpass and on the Eastside Bridge over the Big Wichita River. The materials used in the repair work were a seven-sack latex-modified concrete with plastic fibers and a seven-sack cementitious concrete. Both the materials were cast at approximately the same time (one year ago) and subjected to the same environmental conditions. All of the overlays were approximately 76 mm deep, with the deteriorated concrete being removed down to the steel. The causes of deterioration included normal maintenance and de-icing salts. The cementitious materials had an average bond strength of 0.7 MPa ($\sigma = 0.3$) and showed no signs of durability problems. The latex-modified material had a higher bond strength of 0.9 MPa ($\sigma = 0.6$), but had delamination occurring along its edges.

Table 6.12 Background information for Wichita Falls No. 2

Desired Information	Description
Geographic Location	Scott St. overpass and Eastside bridge
Age of Repair	1 Year
Repair Location	Top of bridge deck
Repair Material	Latex-modified with plastic fibers and cementitious material
Orientation	Horizontal
Repair Thickness	≅ 76 mm
Exposure Conditions	Subjected to direct traffic loading and environmental conditions

6.8 SAN ANGELO SITE VISIT

The repair evaluated is located on the underside of an overpass along Beauregard near the Santa Fe Park. Damage consisted of spalling and chipped areas on bent caps, columns, and backwalls. The repair system consisted of a three-part process. Initially an epoxy primer was applied, then a seven-sack (305 kg) cementitious mix (consisting of grade 1 fine aggregate or grade 7 coarse aggregate) was added, depending on the thickness of the repair, followed by an epoxy grout covering. Most of the repairs evaluated were approximately 38 mm in depth.

Table 6.13 Background information for San Angelo

Desired Information	Description
Geographic Location	Beauregard overpass near the Santa Fe park
Age of Repair	5 Years
Repair Location	Pier caps, columns and backwalls
Repair Material	Cementitious material
Orientation	Vertical
Repair Thickness	≅ 38 mm
Exposure Conditions	Protected by bridge deck

The repairs were 5 years old and in good condition. The average pull-off strength was 1.0 MPa (σ = 0.4), with the cores failing at the bond interface. Figures 6.9 and 6.10 show typical vertical coring and vertical pull-off test being conducted.

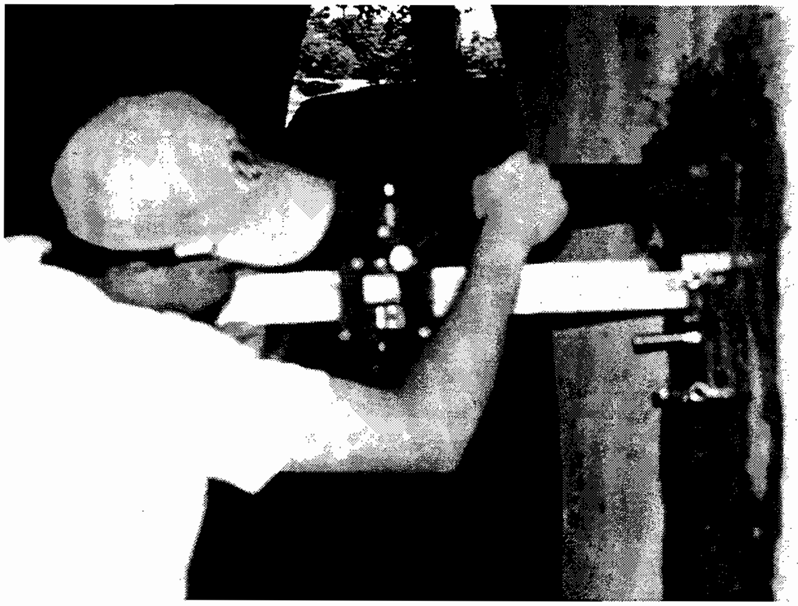


Figure 6.9 Vertical coring of column — San Angelo

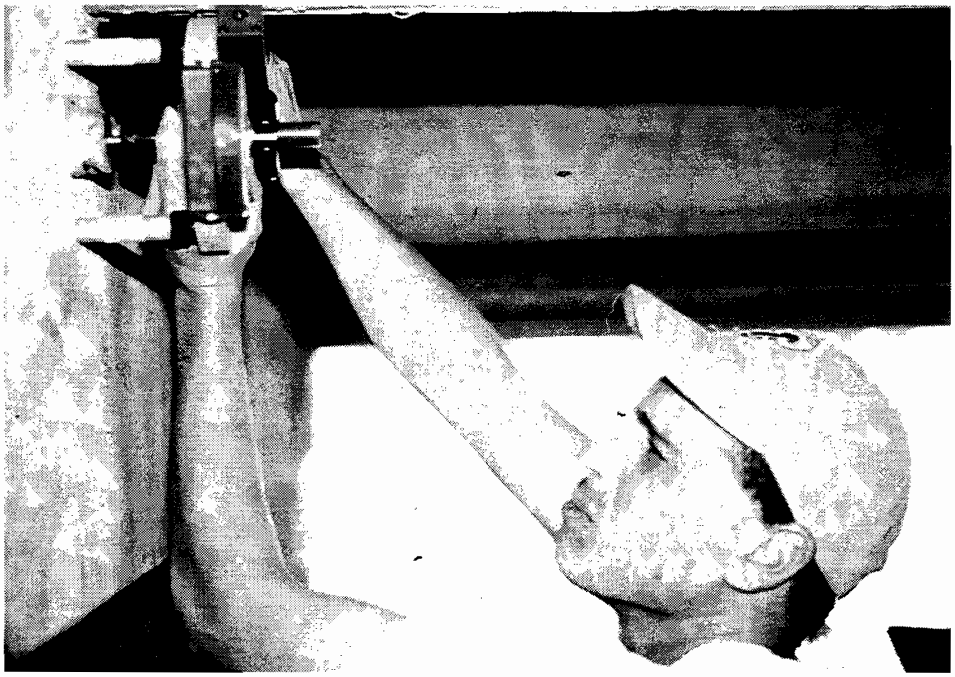


Figure 6.10 Pull-off test being conducted on vertical surface — San Angelo

6.9 LUFKIN SITE VISIT

There were two separate sites evaluated in Lufkin, denoted as Lufkin No. 1 and No. 2.

6.9.1 Lufkin No. 1

The repair is located on a bridge deck along US 59 at the Trinity River (Figure 6.10). The damage was caused by a truck fire 8 years ago. A damaged concrete area 1.5 m by 6.0 m had been removed to a depth of 51 mm. A rapid-setting cementitious material had then been placed down. The repair was visually in good condition. Five cores were taken and had an average pull-off strength of 0.9 MPa ($\sigma = 0.2$). Two of the cores failed along the bond interface, two failed in both the substrate and repair materials, and one failed within the substrate.

Table 6.14 Background information for Lufkin No. 1

Desired Information	Description
Geographic Location	US 59 over the Trinity River
Age of Repair	8 Years
Repair Location	Top of Bridge Deck
Repair Material	Cementitious
Orientation	Horizontal
Repair Thickness	51 mm
Exposure Conditions	Subjected to direct traffic loading and environmental conditions

Figure 6.11 Horizontal coring of repaired bridge deck — Lufkin No. 1

6.9.2 Lufkin No. 2

The second repair site visited was along US 190 on the underside of a bridge over Menard Creek. The areas repaired were spalled bent caps. The repair material was an epoxy extended with sand. The repairs were 12 years old and had significant cracking and spalling present (Figure 6.11). Based on sounding of the concrete, about half of every repaired area appeared to be delaminated. As a result, there was a large variance in pull-off strengths. The strengths varied from 0.4 MPa to 3.4 MPa ($\sigma = 1.1$). Of the five cores taken, four failed at the bond interface and one failed in the substrate.

Table 6.15 Background information for Lufkin No. 2

Desired Information	Description
Geographic Location	US 59 at the Menard Creek
Age of Repair	12 Years
Repair Location	Bent caps
Repair Material	Epoxy
Orientation	Vertical
Repair Thickness	0 mm to 38 mm
Exposure Conditions	Protected by bridge deck

Figure 6.12 Spalling of repaired bent caps — Lufkin No. 2

6.10 PRESIDIO SITE VISIT

This repair involved a prestressed I-beam that had been damaged during transport from the fabricator to the job site. The damage, which occurred at the location of a support during transport, was in the form of spalling up to 51 mm deep, exposing a steel strand. On the job site, the beam was repaired using mechanical anchors and epoxy (TxDOT Type VIII) extended with sand. Approximately 2 to 3 years after the repair was made, it completely delaminated (Figure 6.12). The failure plane occurred within the substrate.

Table 6.16 Background information for Presidio

Desired Information	Description
Geographic Location	US 67 over Cibilo Creek
Age of Repair	5 Years
Repair Location	Flange of an I-beam
Repair Material	Epoxy
Orientation	Vertical
Repair Thickness	0 mm to 51 mm
Exposure Conditions	Protected by bridge deck

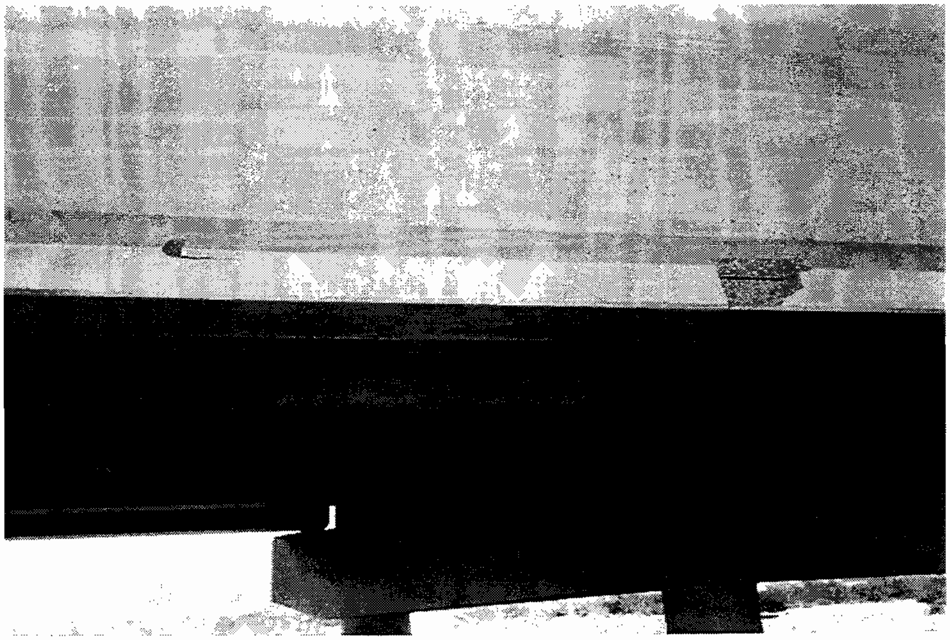


Figure 6.13 Delamination of repaired I-beam — Presidio

6.11 VICTORIA SITE VISIT

The repairs in Victoria were located on damaged U-beams at a precast plant. The damage included voids (from lack of consolidation), forms that slipped during casting, indentations created from footprints, and beam corners that chipped during transport from the plant.

There were six different repairs evaluated during the site visit. The age of the repairs ranged from 2 days to 1-1/2 years. The primary reason this location was selected was because it was possible to perform pull-off tests of young repairs. This allowed for the repair pull-off strength to be found before being subjected to substantial amount of environmental conditions and aging. This site visit made it possible to find the initial repair strengths before the precast element was transported to the job sites. At this particular plant, two types of repair materials were primarily used. For larger and deeper repair areas, a cementitious material — Emaco S88-CA — was used. For any large vertical repairs, formwork was also utilized. For the smaller repairs, TxDOT Type VIII epoxy extended with sand was used.

As would be expected, all the materials appeared to be in excellent condition. There was no sign of deterioration on any of the repairs. Table 6.17 provides background information and the pull-off strengths for each of the repairs. The number of cores taken at each location ranged from 1 to 5, depending on the size of the repair. When the repair area was large enough, a minimum of three cores was obtained.

For the cementitious repair material, the average pull-off strengths for the two repairs were 1.5 MPa and 3.0 MPa, with all failures occurring at the interface. The lower value corresponds to a repair performed 1-1/2 years ago, and the higher value to a 5-month-old repair. It is possible that some loss of strength resulted from the repair being subjected to direct environmental conditions for a longer period of time.

The pull-off strengths for the four epoxy repairs ranged from 1.3 MPa to 2.8 MPa. Three of the repairs had values of approximately 1.5 MPa, with failures at the interface. The epoxy repair with the largest pull-off strength of 2.8 MPa differed from the other repairs because it was much thinner (3 mm to 6 mm). Another difference was that the mode of failure for the thinner repair occurred in both the interface and substrate. The damage was due to the form at the end of the beam slipping during casting and causing the beam to become slightly uneven.

It was expected that the pull-off strengths for the epoxy repairs would have more variance because there were no specified mix proportions used (as there were for the prepackaged Emaco S88-CA). The epoxy mix consisted of adding dry sand to the epoxy until the desired working consistency was obtained. The mix consistency can differ depending on whether a horizontal or a vertical surface is being repaired. All the epoxy repairs were less than 1 month old.

The pull-off strengths obtained during this site visit provide good starting points for establishing bond strengths of a new repair prior to being subjected to substantial deteriorating environmental conditions. This type of information is pertinent if any type of quality control for repair work is to be established.

Table 6.17 Background information for Victoria

Desired Property	**Victoria No. 1**	**Victoria No. 2**	**Victoria No. 3**	**Victoria No. 4**	**Victoria No. 5**	**Victoria No. 6**
Age of Repair	1-1/2 Years	2 to 3 Days	2 to 3 Days	5 Months	7 Days	1 Month
Repair Location	Inside of U-beam	Top of U-beam	Top of U-beam	Top of U-beam	Top of U-beam	End of U-beam
Repair Material	Cementitious	Epoxy with sand	Epoxy with sand	Cementitious	Epoxy with sand	Epoxy with sand
Orientation	Horizontal	Vertical	Vertical	Vertical	Vertical	Vertical
Size of Repair (mm)	(381 to 610) by 3353	152 by 305	152 by 305	152 by 610	152 by 914	1219 by 1524
Repair Thickness (mm)	51	38	38	51	51	3 to 6
Average Pull-Off Strength (MPa)	1.5	1.3	1.6	3.0	1.5	2.8
Standard Deviation (MPa)	0.4	0.3	0.3	0.6	0.4	0.7

Figure 6.14 Coring repaired corner of U-beam — Victoria No. 6

6.12 LABORATORY TESTS OF FIELD SPECIMENS

It was desirable to determine the coefficient of thermal expansion (CTE) of the repair materials evaluated in the field. The specimens used in the CTE tests consisted of the cores collected from the pull-off tests. It was not possible to obtain samples for all the site visits, owing to many of the repairs being too thin. The cores were initially sliced into approximately 25-mm disks. Then, two 30-mm strain gages were attached to the flat sides of the specimens. Using the procedures outlined elsewhere (Ref 16), companion strain gages were also connected to fused quartz, of which the CTE was known. The specimens were then cycled between 22°C and 100°C until the reproducible results presented in Table 6.23 were obtained. The values show that there exist large differences in CTE between the polymer-based materials and the cementitious materials. This type of incompatibility can lead to the development of large thermally induced stresses, most likely leading to premature failures.

Table 6.18 Coefficient of thermal expansion of field specimens

Geographic Location	**Repair Material Type**	**CTE of Repair Material ($\times 10^{-6}$ /°C)**
Austin No. 3	Epoxy	27
Fort Worth No. 1	Substrate Epoxy	3.1 20
San Angelo	Substrate Cementitious	3.2 6.5
Victoria	Epoxy Cementitious	15 3.8
Wichita Falls No. 1	Latex-Modified	20

6.13 EFFECT OF CORE DIAMETER ON PULL-OFF STRENGTH

During the field evaluation program, we noticed that the diameter of the core seemed to have an effect on the observed pull-off strength. This was first noticed when 51-mm cores were used during the Fort Worth No. 1 site visit; an attempt was then made to correlate the results back to a previous study that had used 102-mm diameter cores. It was found that the values for the 51-mm cores were consistently higher than those documented in the previous report using 102-mm-diameter cores. In addition to the difference in core diameter, the pull-off tester used was also different.

In order to determine the cause of the discrepancies, we performed laboratory tests to develop a correlation between the pull-off strengths obtained for the 51-mm and 102-mm diameter cores. The laboratory tests consisted of obtaining twelve cores for both the 51-mm and 102-mm diameter cores on the same concrete specimen (Figure 6.14). Pull-off tests were then conducted to determine the bond strengths for each size. From the results it was found that the 51-mm-diameter bond strengths were consistently about 35 percent higher than those for the 102-mm diameter cores. The 51-mm diameter cores showed a greater precision, with very little variance in pull-off strengths. The 102-mm cores had a larger variance but still showed consistency in the results.

To compare the loads recorded by the pull-off testers, we attached the two devices to one another and read the tensile load simultaneously on both. The results revealed that each tester read approximately the same tensile value, within 0.35 MPa of each other. The accuracy was limited by the scales for each testing device. Another factor that could cause discrepancies in pull-off strengths is the size of aggregate that is present in the concrete that is being cored.

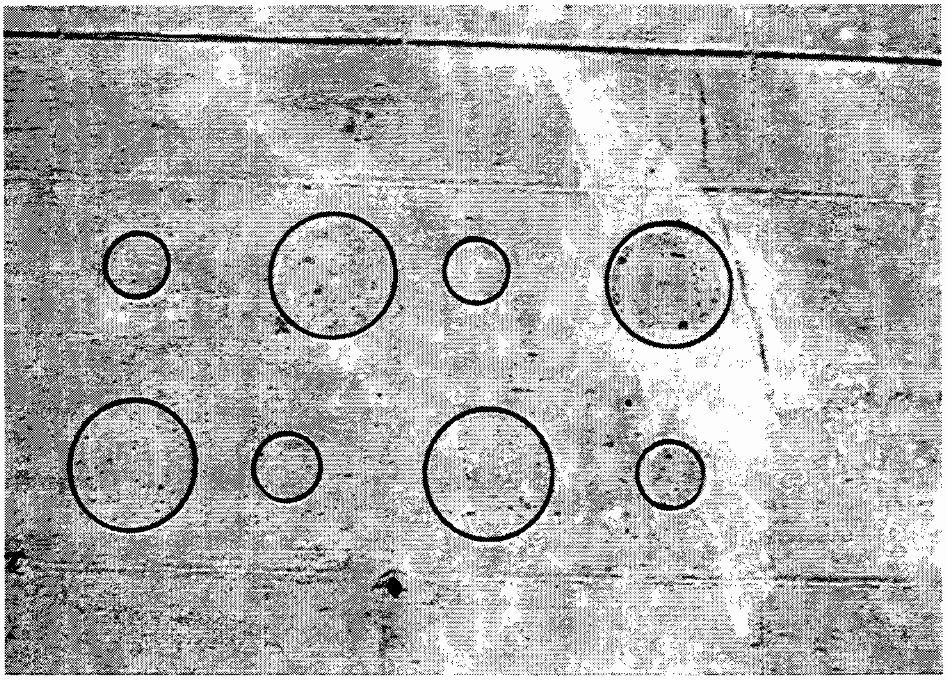


Figure 6.15 51-mm and 102-mm cores used for correlation tests

6.14 CONCLUSION

Overall, we evaluated a wide range of typical repairs found in Texas. A comparison of the field evaluation sites is presented in Table 6.23. The two most common locations where repair work is performed are the top of a bridge deck and the pier caps (particularly in the region directly under a beam). The procedures typically followed for these two repairs are quite different. A cementitious, latex-modified or possibly a polymer material is normally used to repair a bridge deck. The substrate is typically removed to a depth of 51 mm and the repair area is usually large. One of the primary concerns for these repairs is the time required for the material to gain its strength and enable the area to be reopened to traffic. The other commonly observed repair involved spalling pier caps. Epoxy grout or a cementitious material was used most often, with an exterior weatherproofing material applied over the top surface. The thickness of each repair varied from a featheredge up to 51 mm in depth. The primary concerns for this repair are achieving a good bond and consolidation for the vertical repair.

It is difficult to make generalizations about the repairs evaluated, owing to there being so many different variables involved. What can be said is that most of the repairs at least 1 year old had an average pull-off strength of approximately 0.9 MPa. This was found to be true regardless of the type of repair material and orientation of the repair. The primary problem observed for the repairs was delamination. For most of the older repairs, it was necessary to sound the repair with a hammer in order to locate areas where a pull-off test could be performed. Often the material appeared to be performing well, but, after a closer investigation, it was found that the repair material could be easily chipped free from the parent concrete. A higher bond strength was observed for materials that were under a year old. These values were anywhere from 50 percent to 300 percent higher than those of the older repairs.

Based on the results and observations gathered during the site visits, the widespread use of epoxy grouts to repair vertical spalls may not be the most appropriate choice. The primary reasons for their use is that the epoxy repair materials can be easily applied to vertical surfaces and are capable of achieving high initial bond strengths. The problem observed is that the repairs are unable to serve their intended purposes for an extended period of time. Epoxy materials are more expensive than other typically used repair materials and need to last longer and perform better in order to be justified economically. A better economical solution may be the use of a cementitious or latex-modified repair material if the repair is made in a location where large thermal cycles can be expected. The reason these types of materials have not been used in the past is that they are typically more difficult to apply to vertical surfaces. In order for these types of materials to be successful, an appropriate mix design and experienced personnel need to be utilized. If not, low bond strengths can be expected (as observed during the Amarillo site visit).

Another observation made during the site visits was that, if performed correctly, the bond strengths for polymer overlays were 2 to 3 times larger than those associated with cementitious or latex-modified based repairs. The problem recognized with the use of polymer materials is that people typically have less experience using polymer materials; as a result, their use can make the repair more prone to errors. Polymers should strongly be considered in repair locations that do not experience large temperature fluctuations. A cementitious material may be more appropriate: (1) if the repair is more than 25-mm deep; (2) the personnel have past success using a cementitious mix; or (3) for economic reasons. A high bond strength is not always necessary if the compatibility properties of the repair material closely match those of the substrate.

Figure 6.16 shows the effect of age on the average pull-off strength measured during the field site visits. The plot has also been broken down by the type of repair material evaluated at each location. From the figure it is obvious that the pull-off strength can vary widely for all types of repair materials, independent of the repair age. This shows that there are factors other than age that have more influence on the bond strength. Two other factors that may influence the bond strength not accounted for in this figure are the quality of workmanship and the environmental conditions. Given identical repair materials, it is possible for an 8-year-old repair to have a bond strength higher than that of one that is only a couple of years old. This can be attributed to the quality of workmanship or environmental conditions that the repair is subjected to during its service life. Excluding a few new repairs and some polymer-based materials that exhibited a high pull-off strength even after 5 years, the majority of repairs had pull-off strengths below 2.0 MPa regardless of age.

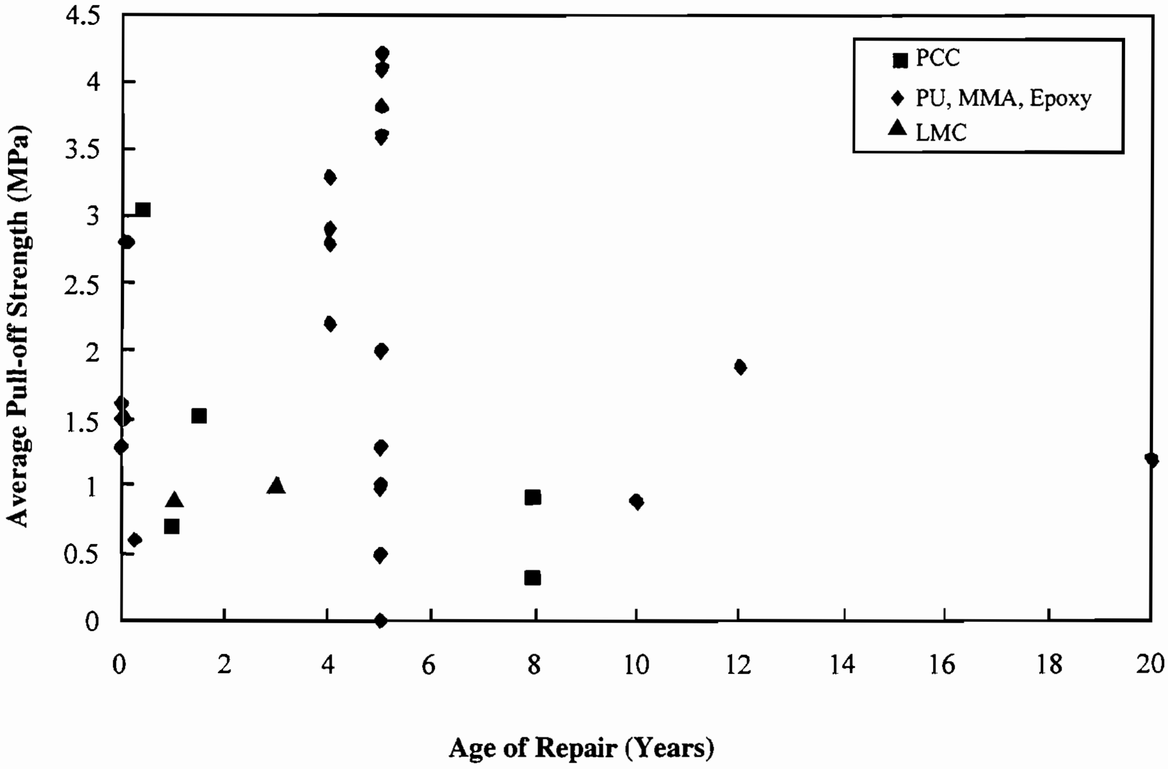


Figure 6.16 Effect of age upon pull-off strength

A factor that can ultimately have the largest impact on performance is the quality of workmanship. Unfortunately, it is often difficult to determine if a repair failed as a result of environmental conditions or as a result of poor workmanship or both. In order to obtain good workmanship, it is necessary to select the most appropriate material based on the temperature at placement and type of application. For example, if a mix for a vertical repair is not sufficiently stiff, then the repair is likely to fail. It is also necessary to have well-trained, experienced personnel to perform the repair work. The final step is to properly cure the repair area based on the type of material and weather conditions. If these steps are not followed, then obtaining a high quality repair is impossible. No matter how exceptional the selected repair material is, if it is not applied correctly then the repair will not perform well.

The pull-off strength values obtained during the site visits were typically one-half to one-third the values observed in the laboratory. This discrepancy is larger than would be expected, even when accounting for the laboratory being a controlled environment. The strengths obtained in the laboratory can act as an upper bound for the potential values that can be achieved in field applications. This large gap in strengths can be substantially narrowed if the selection and placement of the repair process are better understood. One way this will be achieved is by creating repair material specifications. These guidelines will enable the field strengths to become closer to the laboratory results by offering better guidelines to an engineer in selecting a repair material. The specifications will account for the environment the repair will be subjected to and lead to the selection of the material that has the best chance for success.

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

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY

As the number of concrete repairs increases, more information regarding repair materials will be required in order to ensure that the most appropriate concrete repair material is selected. Unfortunately, there is currently little guidance available to an engineer who must select a repair material to meet the environmental demands and loading conditions that it will be subjected to throughout its lifetime. There is some indication that organizations like ICRI will in the near future develop standard repair specifications. These specifications will permit the selection of a repair material that has a much higher probability of success than those that do not conform to the specifications.

7.2 CONCLUSIONS

This study has conducted a laboratory and field evaluation of the pertinent material properties that are necessary for establishing repair material specifications. This is the second report of the 3-year research study. The first report focused on determining the current state of the art of concrete repair throughout North America. It included a thorough literature search and a general information survey to obtain a database of information about the concrete repair field. Also, a preliminary material selection process was developed.

This study has been more concerned with testing the pertinent repair material properties. An extensive laboratory evaluation program was conducted to obtain the material properties of the various repair materials. Actual repairs made throughout Texas were also investigated during the field evaluation program. This program made it possible to observe repairs made with different materials that have been subjected to a variety of deteriorating mechanisms. The third report will focus on the development of repair material specifications. Guidelines and methods to ensure the quality of the repairs will also be included in the report. The specifications will be based on information and data obtained from the first two reports. The ultimate goal is to have a working document that will aid engineers in the repair material selection process. The following sections present important conclusions obtained from the laboratory and field evaluation programs.

7.3 SUMMARY OF LABORATORY EVALUATION PROGRAM

- Nine different proprietary repair materials were tested: Three PCC, one MPC, two epoxy PC, one MMA PC and two LMC.

7.3.1 Mechanical Properties

- Three different categories of material properties were evaluated in this testing program: mechanical, compatibility, and durability.

- Mechanical property results showed that the majority of the repair materials currently available have ample compressive strengths (above 35 MPa). As a result, the focus should be on other material properties.
- The polymer-based materials (19 to 22 MPa) had flexural strengths 2 to 3 times that of the PCC and MPC materials (7 to 11 MPa).

7.3.2 Compatibility Properties

- The PCC, MPC, and LMC materials had compatibility properties (modulus of elasticity, shrinkage, and coefficient of thermal expansion) comparable to those of ordinary concrete.
- The polymer-based materials have much different compatibility properties than those of typical substrate. The CTE was found to be 2 to 4 times higher than that of ordinary concrete. The shrinkage for the epoxy PCs were in the same range of the substrate and the other materials tested. The MMA PC experienced shrinkage much greater than that observed for the other materials.
- Coefficient of thermal expansion (CTE) can be decreased for polymer-based materials by adding aggregate to the mix.

7.3.3 Bond Strength

- Extensive thermal cycle testing was conducted using hot (10°C to 35°C) and cold (12.2°C to 15.6°C) thermal cycles. The temperature ranges were chosen to approximate the temperature cycles an actual repair in Texas may be subjected to during its lifetime. The test procedure consisted of coring the specimens after every 4 to 6 weeks (112 to 168 thermal cycles) and conducting pull-off tests. The majority of materials tested did not lose significant bond strength when subjected to thermal cycles. The only specimens to fail were those with neat epoxy mixes. The results indicate that a large mismatch in CTE (as for the neat epoxy specimens) between the repair material and substrate can lead to a failure when subjected to thermal cycling.
- Initial pull-off strengths for the PCC and MPC materials were approximately 2.1 MPa, while the epoxy PC, MMA, and LMC materials have initial strengths of about 3.5 MPa.
- The weak link in the repair system for the materials tested is normally the interface bond between the substrate and repair material.
- Pull-off strengths performed on the same material can differ by as much as 0.3 MPa to 0.5 MPa for values of 3 MPa to 4 MPa. This leads to the possibility of a 3 to 12 percent error.
- The diameter of core seemed to have an effect on the observed pull-off strengths. A laboratory test to determine the relationship between core diameters revealed that the pull-off strengths for the 51-mm cores were consistently about 35 percent higher than those with 102-mm cores.
- The only two material properties, based on statistical analysis, that can be used to predict bond strength are the flexural strength and modulus of elasticity. The bond

strength model is best approximated when based on the material's flexural strength. The model had a coefficient of determination of 0.64.

7.3.4 Durability Properties

- The polymer-based materials exhibited excellent durability properties (absorption, abrasion, and permeability). Most of the other materials fared equally except for the MPC material, which had high permeability classification and experienced high weight loss during the abrasion test.

7.4 SUMMARY OF FIELD EVALUATION PROGRAM

- Existing repairs throughout Texas were evaluated both qualitatively and quantitatively. The quantitative evaluation consisted of coring the repair material and performing pull-off tests.
- The CTE for some of the repair materials and their corresponding substrates were determined. The substrate typically had values in the range of 3.1 to 3.2 x 10^{-6} mm/mm/°C. The CTE for the repair materials varied from 15 to 27 x 10^{-6} mm/mm/°C for the epoxy materials, to 3.8 to 6.5 x 10^{-6} mm/mm/°C for the cementitious materials.
- Repairs over a year old had average pull-off strengths of 0.9 MPa regardless of the type of repair material and orientation of the repair.
- The primary problem observed for the repairs was delamination. The older the repair, the more severe the delamination.
- Newer repairs (i.e., those less than 1 year old) had pull-off strengths 50 to 300 percent higher than those associated with older repairs.
- It was difficult to determine whether the low bond strengths were a result of environmental conditions or poor workmanship.
- The pull-off strengths obtained in the field were substantially lower than those strengths observed in the laboratory evaluation program.

7.5 RECOMMENDATIONS

This report has provided all the pertinent information and data necessary to develop repair material specifications. The next step would be to create repair guidelines based on this study's results. It would also be necessary to develop quality control methods that will ensure that a repair was performed satisfactorily. The pull-off test method would lend itself well to ensuring quality control and quality assurance of concrete repair work if a minimum pull-off strength and variability were established prior to performing the repair. It would also be helpful to develop a program that placed and monitored actual repairs. The monitoring program would enable the evaluation of the limitations of the laboratory results and any established guidelines. This is important, given the large discrepancy observed between the results obtained in the laboratory and those of actual in-situ repairs.

Ultimately, the selection process would be best suited to a user-friendly, computer-based program. This would allow an engineer to be queried for all the background information about the repair, as a way of ensuring that all essential elements will be considered during the selection process. The computer program could then automatically compile the appropriate material selection criteria that could be used to choose a repair material. By utilizing a computer program, one could draw upon a database that could be continually modified and updated as more information about the repair process is gathered.

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APPENDIX A

MIX PROPORTIONS FOR PROPRIETARY PRODUCTS

DURACAL

CONSTITUENT	NEAT	EXTENDED
DURACAL (kg)	22.6	22.6
WATER (L)	5.7	6.6
COARSE AGGREGATE (kg)	N/A	22.6
SAND (kg)	N/A	22.6

TxDOT CLASS “K”

CONSTITUENT	EXTENDED
TYPE III CEMENT (kg)	96
WATER (L)	19
COARSE AGGREGATE (kg)	270
SAND (kg)	157
SET-ACCELERATOR (ml)	932
WATER REDUCER (ml)	696
AIR ENTRAINMENT (ml)	0.44

EMACO S88-CA

CONSTITUENT	NEAT
EMACO (kg)	25
WATER (L)	3.7

<table>
<tr><th colspan="3">SET 45 HOT WEATHER</th></tr>
<tr><th>CONSTITUENT</th><th>NEAT</th><th>EXTENDED</th></tr>
<tr><td>SET 45 (kg)</td><td>23</td><td>22.7</td></tr>
<tr><td>WATER (L)</td><td>1.9</td><td>1.9</td></tr>
<tr><td>COARSE AGGREGATE (kg)</td><td>N/A</td><td>13.6</td></tr>
</table>

<table>
<tr><th colspan="2">TxDOT TYPE VIII</th></tr>
<tr><th>CONSTITUENT</th><th>EXTENDED</th></tr>
<tr><td>RESIN (kg)</td><td>1.9</td></tr>
<tr><td>HARDENDER (kg)</td><td>1.0</td></tr>
<tr><td>SAND (kg)</td><td>13.6</td></tr>
</table>

<table>
<tr><th colspan="2">BURKEPOXY MORTAR</th></tr>
<tr><th>CONSTITUENT</th><th>EXTENDED</th></tr>
<tr><td>RESIN (L)</td><td>0.95</td></tr>
<tr><td>HARDENER (L)</td><td>0.5</td></tr>
<tr><td>SPECIAL AGGREGATE (kg)</td><td>18</td></tr>
</table>

T17 POLYMER CONCRETE		
CONSTITUENT	**NEAT**	**EXTENDED**
POWDER (kg)	34	34
LIQUID (L)	3.8	3.8
AGGREGATE (kg)		
MIX 1	N/A	17
MIX 2 (For 3.81 cm Bond Tests)	N/A	34

SIKATOP 122		
CONSTITUENT	**NEAT**	**EXTENDED**
POWDER (kg)	27.7	27.7
SBR/WATER (L)	3.8	3.8
AGGREGATE (kg)	N/A	19

BURKE-KRETE	
CONSTITUENT	**NEAT**
POWDER (kg)	18
SBR/WATER (L)	3.8